Modelling Irrigation Water Management under Water Shortage and Salinity Conditions

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Abstract

Establishment of efficient irrigation and drainage management for sustainable crop production can be a complex process because of the interactions that exist between the system variables involved such as the crop, soil water, and hydroclimatic conditions. Mathematical modelling has been recognised as a useful approach in the assessment of the impact of different irrigation and drainage practices on crop yield. The usefulness of mathematical models in identifying efficient management strategies under uncertain conditions is, however limited by the theories used in models as well as by the availability and quality of field data that can be used in the calibration and validation of these models. Many models have been developed and used to simulate water and solute flux in the crop rootzone. This thesis describes the development and application of the WAVE model to simulate water and solute transport in the vadose zone and their effect on crop transpiration and yield.

The WAVE model was modified to include the effect of salinity on crop transpiration, and used to simulate soil water balances, to investigate long-term salinity build-up in the root zone, and in conjunction with a crop yield response model to assess their effect on crop yield. The practicality of the modelling approach in the establishment of optimal irrigation and drainage practices is considered through application to the Makhtaaral region of South Kazakhstan. The impact of several irrigation and drainage scenarios was evaluated. Optimal irrigation and drainage strategies for sustainable crop production have been derived.

For the problem considered in this study, the WAVE model, along with the crop yield response model, can be used as a tool for assessing the impact of different irrigation and drainage scenarios on crop yield. The results demonstrate that the modelling approach is robust and applicable under arid and semi-arid conditions and to a wide range of water shortage and salinity conditions.

Declaration of originality

I declare that this thesis is my original work except where stated otherwise. The work presented herein has been conducted by myself under the supervision of Dr. Robin Wardlaw in the Institute of Infrastructure and Environment, School of Engineering and Electronics, at the University of Edinburgh, Edinburgh, United Kingdom between October 2001 and June 2006. The work presented in this thesis has not been submitted for any other degree or professional qualifications.

Mohamed Al-Azhari M. Saleh

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Dedicated to my family

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Contents

Abstract........ii
Declaration of originality........iii
Acknowledgements........v
Contents........vi
List of figures........xi
List of tables........xvii
Acronyms and abbreviations........ xix

1. INTRODUCTION........1
1.1 Introduction........1
1.2 Problem Statement........2
1.3 Kazakhstan........4
1.4 The WRMLIP Project........5
1.4.1 Irrigation System........7
1.4.2 Drainage System........8
1.4.3 Recent Irrigation Practices........9
1.5 The Need for Mathematical Modelling........9
1.6 Motivation for Work........12
1.7 Thesis Objectives........13
1.8 Thesis Contributions........13
1.9 Thesis Organisation........14

2. LITERATURE REVIEW........16
2.1 Introduction........16
2.2 Evapotranspiration........17
2.2.1 Definition........17
2.2.2 Reference Crop Evapotranspiration........17
2.2.3 Evapotranspiration under Non-standard Conditions........19
2.2.4 Soil Water and Salinity Stress........20

2.2.5 Approaches for Use with Variably Saturated Flow Modelling............22
2.3 Yield-water Relationships..25
2.3.1 Water Use Efficiency..25
2.3.2 Crop Water Production Functions..28
2.3.3 Irrigation Scheduling..32
2.3.4 Effect of Irrigation Scheduling on Yield and Water Use Efficiency......35
2.4 Salinity affect...37
2.4.1 Introduction...37
2.4.2 The Effect of Salinity on Crop Transpiration and Yield....................38
2.4.3 Irrigation Water Management for Salinity Control..........................45
2.5 Conclusions...46

3. EVALUATION OF CROP YIELD RESPONSE FUNCTIONS...48

3.1 Introduction...48
3.2 Assessment of Crop Yield Response Functions.................................51
3.3 Conclusions...59

4. VARIABLY SATURATED FLOW MODELS..........................61

4.1 Introduction...61
4.2 Models Overview...62
4.3 Process Description..64
4.3.1 Variably Saturated Flow...64
4.3.2 Evapotranspiration...68
4.3.3 Solute Transport..70
4.3.4 Crop Yield Response...73
4.4 Strength and Weaknesses...74
4.4.1 WAVE...74
4.4.2 UNSATCHEM..75
4.4.3 WAVES...76
4.4.4 SWAP...76
4.4.5 HYDRUS-2D and UNSATCHEM..78

4.4.6 SALTMED.....78
4.4.7 Significant Model Differences.....79
4.5 Model Application.....83
4.5.1 Applications: Evapotranspiration.....83
4.5.2 Applications: Irrigation Scheduling.....84
4.5.3 Applications: Salinisation.....86
4.5.4 Applications: Solute Transport.....88
4.6 Conclusions.....89

5. THE WAVE MODEL.....91

5.1 Introduction.....91
5.2 The WAVE Model Theory.....92
5.2.1 General.....92
5.2.2 Model Structure.....92
5.2.3 Space and Time Scales.....93
5.2.4 The Water Transport Module (WAT).....94
5.2.5 Estimation of Potential Crop Evapotranspiration.....96
5.2.6 The Solute Transport Module (SOL).....98
5.3 Model Inputs.....99
5.4 The WAVE model Interfaces and Utilities.....101
5.4.1 Introduction.....101
5.4.2 The C_YIELD model.....101
5.4.3 Pre-processing.....104
5.4.4 Post-processing.....109
5.5 The Modified WAVE Model-WAVE_MS.....105
5.6 Conclusions.....119

6. THE WAVE MODEL SET-UP AND CALIBRATION.....121

6.1 Introduction.....121
6.2 Field Data.....122
6.3 Data Available.....132
6.3.1 Meteorological Data.....132

6.3.2 Soil Characteristics....135
6.3.3 Crop Characteristics....137
6.3.4 Recent Irrigation Practices....142
6.4 WAVE Model Parameterisation....144
6.4.1 Water Transport Parameters....144
6.4.2 Solute Transport Parameters....146
6.5 WAVE_MS Model Calibration....147
6.5.1 General....147
6.5.2 Methods of Establishing Simulation Quality....147
6.5.3 Fitting Soil Moisture Retention Curves....151
6.5.4 Soil Moisture Content Calibration....156
6.5.5 Soil Moisture Tension....173
6.5.6 Soil Salinity....177
6.6 Conclusions....188

7. APPLICATION OF THE WAVE MODEL TO THE MAKHTAARAL REGION OF SOUTH KAZAKHSTAN....189

7.1 Introduction....189
7.2 Evaluation of the Current Irrigation and Drainage Management....189
7.2.1 Crop Water Requirements....190
7.2.2 Soil Salinity....192
7.2.3 Crop Yield....197
7.3 Establishment of Optimum Irrigation and Drainage Strategies....200
7.3.1 Management Variables....200
7.3.2 Cost of Irrigation and Drainage....200
7.3.3 Description of Scenarios....202
7.4 Scenario Evaluation....206
7.4.1 Crop Water Requirements....206
7.4.2 Salinity Build up....208
7.4.3 Crop Yield....214
7.4.4 Sustainability....217
7.4.5 Identifying the Optimum Irrigation and Drainage Scenarios....223

7.4.6 Wider Issues....226
7.5 Conclusions....228

8. CONCLUSION....230
8.1 Introduction....230
8.2 Achievement of the Research....230
8.3 Limitations of the Research....235
8.4 Recommendations for Further Research....235
8.4.1 Field Data Collection....235
8.4.2 Crop Transpiration....236
8.4.3 Crop Yield....236
8.4.4 General Modelling Capability....236

References....238

Appendices....260
A. The Modified WAT_UPT.FOR Source Code....260
B. The source code for the new subroutine CROP_CHAR.FOR....266
C. Irrigation and Drainage Scenarios....267
D. The WAVE Model Results....270
E. The Prediction Runs Output....293

List of figures

1.1 Map of Kazakhstan..6
1.2 The WRMLIP project location...10
3.1 Comparison of yield response functions for sorghum..............................53
3.2 Comparison of yield response functions for cotton.................................53
3.3 Comparison of yield response functions for sorghum using Doorenbos and Kassam seasonal coefficient...54
3.4 Comparison of yield response functions for cotton using Doorenbos and Kassam seasonal coefficient...54
3.5 Sorghum yield reduction in different stages of crop growth........................55
3.6 Sorghum yield reduction in different stages of crop growth........................56
3.7 Cotton yield reduction at different stages of crop growth...........................56
3.8 Cotton yield reduction at different stages of crop growth...........................57
3.9 Observed and predicted wheat yields under different water stress levels........59
5.1 Schematic representation of the WAVE model modules...........................93
5.2 Concept of vertical space scale..94
5.3 Simple relationship between yield and salinity....................................102
5.4 Relationship between ECe and soil salinity...103
5.5 The data input / editing screen: Soil data..107
5.6 The data input / editing screen: Groundwater data................................108
5.7 The data input / editing screen: Crop and irrigation data.........................109
5.8 The view results screen..111
5.9 Modelled cotton ET using original and modified WAVE model versions (1990-1994)...115
5.10 Modelled cotton ET using original and modified WAVE model versions (1999)..115
5.11 Seasonal cotton transpiration using original and modified WAVE model versions (1990-2000)...116

5.12 Soil moisture content in the rootzone using original and modified
WAVE model versions (1990-1994)...117
5.13 Soil moisture content in the rootzone using original and modified
WAVE model versions (1995-2000)...117
5.14 Groundwater depth using original and modified WAVE model versions
(1995-2000)...118
6.1 Pilot area locations...124
6.2 Sampling locations at Birlik...125
6.3 Sampling locations at Makhtali..126
6.4 Sampling locations at Karaoi...127
6.5 Location of equipment at Birlik..129
6.6 Location of equipment at Makhtali...130
6.7 Location of equipment at Karaoi...131
6.8 Mean monthly air temperature...133
6.9 Mean monthly rainfall..133
6.10 Mean monthly wind speed...134
6.11 Mean relative humidity of air..134
6.12 Mean daily reference crop evapotranspiration..............................135
6.13 Changes in Salinity, Phase I Project Area......................................140
6.14 Changes in Salinity, Phase II Project Area.....................................140
6.15 Fitted soil moisture retention curves, Karaoi area..........................145
6.16 Schematic representation of the WAVE model calibration procedure..........148
6.17 Soil moisture retention curve, Birlik, location P3,
300 and 600 mm depth..153
6.18 Soil moisture retention curve, Birlik, location P3,
1000 and 1500 mm depth...153
6.19 Soil moisture retention curve, Karaoi, location P6,
300 and 600 mm depth..154
6.20 Soil moisture retention curve, Karaoi, location P6,
1000 and 1500 mm depth...154
6.21 Soil moisture retention curve, Makhtali, location P9,
300 and 600 mm depth..155

6.22 Soil moisture retention curve, Makhtali, location P9,
1500 mm depth....155
6.23 Birlik, location P3 Initial Run–Soil Moisture 0-200 mm....157
6.24 Makhtali, location P9 Initial Run–Soil Moisture 0-200 mm....158
6.25 Makhtali, location P9 Initial Run–Soil Moisture 600-8000 mm....158
6.26 Birlik, location P3 Initial Run–Soil Moisture 200-400 mm....159
6.27 Birlik, location P3 Initial Run–Soil Moisture 400-600 mm....159
6.28 Karaoi, location P3 Initial Run–Soil Moisture 200-400 mm....160
6.29 Karaoi, location P3 Initial Run–Soil Moisture 400-600 mm....160
6.30 Makhtali, location P9 Initial Run–Soil Moisture 400-600 mm....161
6.31 Birlik, location P3 Calibration Run–Soil Moisture 200-400 mm....162
6.32 Birlik, location P3 Calibration Run–Soil Moisture 600-8000 mm....162
6.33 Karaoi, location P3 Calibration Run–Soil Moisture 0-200 mm....163
6.34 Karaoi, location P3 Calibration Run–Soil Moisture 200-400 mm....163
6.35 Makhtali, location P9 Calibration Run–Soil Moisture 0-200 mm....164
6.36 Makhtali, location P9 Calibration Run–Soil Moisture 400-600 mm....164
6.37 Birlik, location P3 Calibration Run–Soil Moisture Retention Curve,
300 & 600 mm....168
6.38 Makhtali, location P9 Calibration Run–Soil Moisture Retention Curve,
300 & 600 mm depth....168
6.39 Karaoi, location P3 Calibration Run–Soil Moisture Retention Curve,
1000 & 1500 mm depth....169
6.40 Makhtali, location P9 Calibration Run–Soil Moisture Retention Curve,
1500 mm depth....169
6.41 Soil moisture simulated using the two WAVE model versions, Birlik,
location P3 (0-200 mm depth)....170
6.42 Soil moisture simulated using the two WAVE model versions, Birlik,
location P3 (200-400 mm depth)....171
6.43 Soil moisture simulated using the two WAVE model versions, Makhtali,
location P9 (400-600 mm depth)....171
6.44 Soil moisture simulated using the two WAVE model versions, Karaoi,

location P3 (0-200 mm depth)........172
6.45 Soil moisture simulated using the two WAVE model versions, Karaoi, location P3 (400-600 mm depth)........172
6.46 Soil moisture tension at Birlik (300 & 600 mm depth)........174
6.47 Soil moisture tension at Birlik (1000 & 1500 mm depth)........175
6.48 Soil moisture tension at Karaoi (300 & 600 mm depth)........175
6.49 Soil moisture tension at Karaoi (1000 & 1500 mm depth)........176
6.50 Soil moisture tension at Makhtali (300 & 600 mm depth)........176
6.51 Soil moisture tension at Makhtali (1500 mm depth)........177
6.52 Salinity Build up at Karaoi, location P6 0-200 mm........178
6.53 Salinity Build up at Karaoi, location P6 400-600 mm........179
6.54 Salinity Build up at Karaoi, location P6 600-8000 mm........179
6.55 Impact of irrigation water application on the salinity build up........181
6.56 Impact of irrigation water quality on the salinity build up........181
6.57 Impact of drainage rate on the salinity build up........182
6.58 Impact of leaching amount on the salinity build up........183
6.59 Makhtali site P9 Calibration Run – Soil salinity 400-600 mm........184
6.60 Makhtali site P9 Calibration Run – Soil Salinity 600-8000 mm........185
6.61 Karaoi site P3 Calibration Run – Salinity 400-600 mm........185
6.62 Birlik site P3 Calibration Run – Soil Salinity 0-200 mm........186
7.1 Simulated potential and actual cotton transpiration at Karaoi area, location P3........191
7.2 Simulated potential and actual cotton transpiration at Makhtali area, location P9........192
7.3 Salinity builds up in the rootzone at Makhtali area, location P9........193
7.4 Salinity builds up at Makhtali area, location P9........194
7.5 Salinity build up in the rootzone at Birlik area, location P3........194
7.6 Salinity build up at Birlik area, location P3........195
7.7 Salinity build up in the rootzone at Karaoi area, location P3........196
7.8 Salinity build up at Karaoi area, location P3........196
7.9 Cotton yield at Makhtali area as simulated using modified WAVE_MS Model........198

7.10 Cotton yield at Birlik area as simulated using modified WAVE_MS Model....199
7.11 Cotton yields at Karaoi area as simulated using modified WAVE_MS Model....199
7.12 Reduction in crop transpiration under different irrigation and drainage scenarios at Karaoi area, location P3....207
7.13 Reduction in crop transpiration under different irrigation and drainage scenarios at Birlik area, location P3....208
7.14 Salinity builds up in the rootzone under scenario of low drainage at Karaoi area, location P3....210
7.15 Salinity builds up in the rootzone under scenario of high drainage at Karaoi area, location P3....210
7.16 Salinity build up in the rootzone under scenario of relatively high water application and low drainage at Karaoi area, location P3....211
7.17 Salinity build up at Makhtali area, location P9 under conditions of low water applications and low drainage.... 211
7.18 Salinity build up at Makhtali area, location P9 under adequate irrigation and drainage combinations....212
7.19 Salinity build up at Makhtali area, location P9 under optimum irrigation and drainage combinations....212
7.20 Salinity build up at Birlik area, location P3 under low drainage scenario....213
7.21 Salinity build up at Birlik area, location P3 under optimum irrigation and drainage combinations.... 214
7.22 Crop yield at Makhtali under low water application and poor Drainage....215
7.23 Simulated cotton yield at Karaoi, location P3 under different Scenarios....216
7.24 The effect of drainage timing on crop yield at Karaoi area, Location P3....217
7.25 Cost-Benefit Index for some selected scenarios (Makhtali, location P9)....219
7.26 Cost-Benefit Index for some selected scenarios (Birlik, location P3)....220

7.27 The effect of the recommended scenario on crop yield
at Birlik, location P3........224
7.28 The effect of the recommended scenario on crop yield
at Makhtali, location P9........225
7.29 Salinity build up in the rootzone under optimum irrigation and
drainage combinations at Karaoi area, location P3........225
7.30 The effect of the recommended scenario on crop yield
at Karaoi, location P3........226

List of tables

1.1 Land salinisation in Central Asia..6
1.2 Net irrigation deliveries to the Makhtaaral Region in the vegetation period in recent years..8
2.1 Values of λ_i corresponding to different values of K_y 30
2.2 Sensitivity index (λ) of bread wheat and durum wheat to water stress at different growing stages at Tel Hadya in Syria...........................30
2.3 Classification of waters..39
2.4 Salt tolerance level for fruit crops..39
3.1 Some well-known crop water production function....................................50
3.2 Published seasonal yield coefficients for wheat....................................58
4.1 Input variables and principle model parameters of WAVES......................77
4.2 Summary of input data requirements for SWAP model............................78
4.3 Comparison of the models in each of the five codes presented....................81
5.1 WAVE model input parameters..100
5.2 Contents of the CROP_CHAR.DAT file..104
5.3 Contents of SOIL_STRUCT.DAT file..104
5.4 Simulated cotton yield using original and revised WAVE model versions..119
6.1 Soil monitoring equipment used..128
6.2 Average values of some soil physical characteristics in study locations........138
6.3 Average values of some soil chemical characteristics in study locations.......139
6.4 Growth stages for cotton in pilot Areas..141
6.5 Crop root development in each pilot Area..141
6.6 Leaf area indices used in WAVE Modelling..141
6.7 Leaching applications at modelled locations within the project area, 2001..143
6.8 First Irrigation applications at modelled locations within the project area, 2001..143

6.9 Second Irrigation applications at modelled locations within the project area, 2001..144
6.10 Critical pressure head values used in WAVE modelling..........................146
6.11 Solute transport parameters used in WAVE modelling............................146
6.12 Saturation and residual soil moisture contents.......................................152
6.13 Fitted soil moisture retention curve parameters.......................................156
6.14 Values of the statistical parameters used in the comparison of soil moisture content...166
6.15 Final Calibration Parameters...167
6.16 Values of the statistical parameters used in the comparison of soil salinity....187
7.1 Average observed and simulated cotton Yield in pilot areas, (%)...............197
7.2 Possible irrigation and leaching scenarios..202
7.3 Possible drainage scenarios...203
7.4 Possible irrigation and drainage combinations.......................................205
7.5 Summary of model results, Karaoi soil characteristics............................220
7.6 Summary of Model results, Birlik soil characteristics.............................221
7.7 Summary of Model results, Makhtali soil characteristics.........................222

Acronyms and abbreviations

a_1	weighing factor of water pressure head h $(-)$
a_2	weighing factor of the osmotic pressure head h_o $(-)$
A_1 and A_2	drainage parameters
ADB	Asian Development Bank
A_S	threshold soil electrical conductivity $(dS\ m^{-1})$
AWC	total available soil moisture storage capacity (mm)
b	reduction in yield per increase in EC_e $(\% /\ dS\ \ m^{-1})$
b_e	empirical yield coefficient $(-)$
B_{qh}	empirical parameters $(-)$
B_S	rate at which relative crop yield declines with increasing salinity $(\% /\ dS\ \ m^{-1})$
C	solute concentration $\left(ML^{-3}\right)$
C_f	solute flux concentration $(Kg\ m^{-3})$
C_m	solute concentration in the mobile soil region $(Kg\ m^{-1})$
C_{sm}	adsorbed solute mass on the soil complex $(Kg\ Kg^{-1}\ dry\ soil)$
CBI	Cost-Benefit Index $(-)$
CD	coefficient of determination $(-)$
CRM	coefficient of residual mass $(-)$
D	dispersion coefficient $\left(L^2T^{-1}\right)$
D_r	rootzone soil moisture depletion (mm)
$Drain\_A$	amount of water removed (mm)
EC	European Commission
EC_e	electrical conductivity of the saturation extract for the root zone $(dS\ m^{-1})$

$EC_{ethreshold}$	electrical conductivity at of the saturation extract the threshold of EC_e $(dS\ m^{-1})$
EC_{e50}	EC_e value at which relative yield is 50% $(dS\ m^{-1})$
E_p	potential soil evaporation (L/day)
E	actual evaporation (mm)
EF_2	coefficient of efficiency (–)
ET_a	actual crop transpiration (L/day)
ET_{cadj}	adjusted crop evapotranspiration (L/day)
ET_C	potential crop transpiration (L/day)
ET_m	potential crop transpiration (L/day)
ET_o	reference crop evapotranspiration (L/day)
E_W	fraction of extractable water remaining in the crop root zone (–)
FAO	Food and Agriculture Organisation
g	gravitational constant (L^2T^{-1}),
$GWLOL$	reference position of the water table (L)
h	soil water pressure head (L)
h_s	pressure head at saturation (L)
h_3	soil water pressure head threshold value (L)
h_4	soil water pressure head at wilting (L)
h_{50}	soil water pressure head at which crop transpiration reduced by 50% (L)
$h_{o.50}$	soil solution osmotic pressure head at which crop transpiration reduced by 50% (L)
h_o	soil solution osmotic head (L)
h^*	soil water pressure head threshold (L)
$h_{\max}$	water pressure head at which reduction factor reach minimum value (L)

h_o^*	osmotic head threshold (L)
$h_{o,\max}$	osmotic pressure head at which reduction factor reach minimum value (L)
HI	harvest index $(-)$
I	irrigation water depth (cm)
Irr_A	amount of water applied (mm)
$IWUE$	irrigation water use efficiency $(Kg\ m^{-3})$
J_s	solute mass flux $(Kg\ m^{-2}\ s^{-1})$
K_C	crop coefficient $(-)$
K_{cb}	basal crop coefficient $(-)$
K_d	distribution coefficient $(m^3\ kg^{-1})$
K_e	soil evaporation coefficient $(-)$
K_S	crop stress reduction factor $(-)$
K_W	evapotranspiration reduction coefficient $(-)$
K_y	yield response factor $(-)$
$K(\theta)$	hydraulic conductivity $(L\ day^{-1})$
LAI	leaf area index
$LEPA$	low-energy precision application
L_r	rooting depth (mm)
MAE	mean absolute error (cm^3 / cm^3)
MRC	soil moisture retention characteristics
n	number of observations
n, m	shape parameters
N	number of nodes
O_i	observed value
P	fraction of total available soil moisture that can be depleted from the root zone before soil moisture stress $(-)$
P	precipitation (mm)

P_i	interception amount (L)
P_i	simulated value
p	empirical parameter $(-)$
p_1	empirical parameter $(-)$
p_2	empirical parameter $(-)$
q_w	Darcian water flux $(m^3\ m^{-2}\ day^{-1})$
Q_b	flux across the bottom boundary of the profile
rp_i	proportion of total root mass at node i
rw_i	root water demand at depth node i $\left(m.d^{-1}\right)$
R	water depth lost by runoff (mm)
R^2	pearson type goodness of fit index
RAW	readily available water in the rootzone (mm)
RD	root depth (L)
$RRMSE$	relative root mean square error
S	slope of the relative yield – salinity relationship $(\% /\ dS\ \ m^{-1})$
S_e	effective water content
$Sinksol$	solute sink term $(kg\ day^{-1})$
SRP	sum of numerator overall all nodes
$S(z,h)$	water uptake by plant roots (day^{-1})
T	salinity threshold expressed in $(dS\ \ m^{-1})$
T	transpiration(mm)
TAW	total available water (mm)
TDS	percentage of salts in the soil (by weight)
T_p	potential crop transpiration (L/day)
U	upward capillary into the soil root zone (mm)
UN	United Nations
V	average wind velocity (m/s)

WRMLIP	Water Resources Management and Land Improvement Project
WUE	water use efficiency $(kg/ha/mm)$
X_w	relative availability of water
Y_a	actual crop yield $(Kg\ ha^{-1})$
Y_m	maximum crop yield $(Kg\ ha^{-1})$
Yr	relative yield
$Yrel\_M$	average total relative yield over the last 10 years of simulation $(-)$
z	vertical co-ordinate (L)
$z_{\max}$	maximum rooting depth.
α	inverse of the air entry (L^{-1})
α_{01}	value of α corresponding to $h_{\max}$ $(-)$
α_{02}	value of α corresponding to $h_{o,\max}$ $(-)$
$\alpha(h)$	transpiration reduction factor of the soil water stress $(-)$
$\alpha(h,h_o)$	transpiration reduction factor of the combined soil water and salinity $(-)$
θ	volumetric soil moisture content $(m^3\ m^{-3})$
θ_C	critical soil moisture content $(m^3\ m^{-3})$
θ_{FC}	soil moisture content at field capacity $(m^3\ m^{-3})$
θ_{PWP}	soil moisture content at wilting point $(m^3\ m^{-3})$
θ_r	residual volumetric soil water content $(m^3\ m^{-3})$
λ_i	factor reflects crop sensitivity to water shortage stress $(-)$
ρ	Bulk density (ML^{-3})
ρ_w	density of water (ML^{-3})
Ψ_i	water matric potential (m) at node i
Ψ_{wilt}	matric potential at wilting point (m)
Π_i	osmotic potential (m) at node i
ΔT	difference between maximum and minimum temperature for the day (^oC)

ΔW	change in the soil water content (mm)
ϕ	groundwater level (m)

CHAPTER 1

Introduction

1.1 Introduction

Water is essential for plant growth. It plays an important role in most physiological processes and transports nutrients to the plant from the soil through the root system. When soil moisture in the rootzone is insufficient to meet crop water requirements, crop transpiration and yield decrease below their potential values and the crop is said to be under water stress. In areas of limited water resources, where annual precipitation is not sufficient to meet crop water requirements, irrigation is needed to provide the soil rootzone with adequate moisture to avoid physiological water stress in the crop and to achieve acceptable yield.

The situation becomes more critical when water shortage is combined with salinity problems. Soil salinity is usually caused by irrigating with low quality water or by the upward movement of saline water from a shallow watertable as a result of inadequate drainage. Sustainable crop production can only be achieved if rootzone salinity does not exceed a threshold value, which varies according to crop type. Water shortage and salinity are the major limiting factors to agricultural production under arid and semi-arid conditions. The combined effects of water stress and salinity reduce crop transpiration and result in low yield.

Under these conditions, it is necessary to establish sustainable irrigation and drainage management practices. Establishment of sustainable irrigation and drainage management is complicated by the complex interactions that exist between the crop, soil water, and hydroclimatic conditions. Mathematical models that deal with water and solute transport in the unsaturated or variably saturated zone, along with crop yield response models, can be useful in assessing the impact of different irrigation and drainage practices on crop yield. This is of particular value in areas where water and salinity are the most limiting factors for agricultural production.

Following this introduction, section 1.2 presents the research problem. Section 1.3 gives an introduction to the republic of Kazakhstan and describes the Makhtaaral Region of South Kazakhstan, which is the area considered in this research. Section 1.4 gives general background to the Water Resources Management and Land Improvement Project (WRMLIP), defines the project aims and objectives and outlines the irrigation and drainage systems as well as irrigation and drainage practices that have been used since the early 1990s. Section 1.5 demonstrates the need for mathematical modelling, presents a brief review of the general concepts of existing unsaturated zone models and their importance in the area of irrigation water management. Section 1.6 gives the reasons for undertaking this research and Section 1.7 gives an outline of the objectives of this research. The contributions made in this research are presented in section 1.8. Finally, section 1.9 presents the thesis layout.

1.2 Problem Statement

Global population was 4.4 billion in 1980, 6.5 billion in 2005, and is expect to reach 8.1 billion by 2030 (UNDP, 2005). Population growth is putting increasing strain on water resources, and a major future challenge is in ensuring reliable food production for the growing population. A significant part of expected future population growth will be in arid and semi-arid areas, where water is already a scarce resource, and irrigation essential for crop production. The FAO online database FAOSTAT indicates that between 1961 and 2003, the global area of arable land / permanent crops increased from 1,367 million hectares to 1,541 million hectares. Over the same period, the area of irrigated agriculture increased from 139 million hectares to 277 million hectares. Currently about 18% of the global cropped area is irrigated, but this land is producing about 40% of the global food production (Schultz, 2001). The irrigation sector is thus of vital importance to future food security.

Approximately 50 million hectares of the globally irrigated land is drained (Davis and Hirji, 2003), and this land contributes 10 to 15% of global food production

(Smedema, 2002). Drainage improves agricultural productivity and is required where there is water logging and where salinity is a problem. While the global irrigated area was increasing at a rate of about 2% per year during the 1960s and 1970s, it has now reduced to about 1.4%, partly because irrigated land is going out of production as a result of salinisation (Davis and Hirji, 2003).

Salinity and water logging are the most significant threats to sustainable irrigated agriculture in many parts of the world. Increased agricultural production to meet the needs of a growing global population will come largely from the irrigation sector, but only with improved water management. Estimates of the areas affected by salinity and water logging vary. Szabolcs (1994) has estimated that 40 to 50% of the globally irrigated area is affected by salinity and sodicity caused by poor irrigation and agronomic practices. Konukcu *et al.,* (2005) estimate that about 45 million hectare (16%) of the globally irrigated area suffers from irrigation-induced salinity problems. It has been estimated that about 10 million hectares of agricultural land are lost each year through salinisation and water logging, of which 1.5 million hectares is in irrigated areas (Khan *et al.,* 2006). Irrigation plays an important role in the economies of many countries in arid and semi-arid areas. Around 65% of the globally irrigated area is in Asia. Salinity problems central Asia, China and Pakistan and India are particularly severe.

In the central Asian countries in the Aral Sea Basin - Kazakhstan, Turkmenistan and Uzbekistan, around 22 million people depend upon irrigated agriculture. These countries have some of the largest irrigation schemes in the world (ADB, 1997). However, water shortage and salinity are serious problems. Where water is scarce, there is a tendency not to apply adequate leaching water quantities and if irrigation is with water of poor quality (more than $1000\,mg/litre$ of dissolved salts), salinity build up in the soil horizons in inevitable, and indeed has occurred.

The sustainable management of irrigation and drainage systems to maintain and improve crop production is one of the most significant needs of the rural poor throughout the developing world. Addressing this need requires improved knowledge of processes in the soil horizons, along with improved means of disseminating best practices to farmers, water user groups, and other water management organisations. The best scientific solutions must be brought to the farmers in a manner that is easily understood and applicable by them. This research focuses on achieving efficient irrigation and drainage management for sustainable crop production.

The research focuses on South Kazakhstan which has a serious water shortage, water logging and salinity problems caused by poor irrigation and drainage management. South Kazakhstan provides a suitable case study as recent water management studies have led to the development of a reasonable database of crop and soil characteristics, as well as water management and quality records. The approaches developed as part of this research are generic, although specific recommendations relate to South Kazakhstan.

1.3 Kazakhstan

The University of Edinburgh has been involved with Mott MacDonald (consulting engineers) on the Water Resources Management and Land Improvement Project (WRMLIP) in South Kazakhstan. The project investigated water management practices, and much of the data collected has been available for and widely used in the research described in this thesis. Water shortage and salinity are significant problems in Kazakhstan.

Kazakhstan was one of the former Soviet Union republics and became an independent state in December 1991. It is located in Central Asia, bordered to the west by the Caspian Sea, to the east by China, to the north by Russia; and to the south by Turkmenistan, Uzbekistan and Kyrgyzstan (Figure 1.1). The country is rich in land resources suitable for agricultural production. In 1992 the total planted area was 36.5 million hectares, of which 2.3 million hectare were irrigated. However, more than 33% of this area is affected by salinity (Table 1.1) (Bucknall *et al.,* 2003). In 1990, agriculture was the second largest sector of the Kazakh economy, contributing about 11 percent of the Gross Domestic Product (GDP) (Bucknall *et al.,*

2003) and employing about 17% of the work force (ADB, 1997). Wheat, maize, potatoes, vegetables and grapes are the major food crops planted in South Kazakhstan, in addition to the main industrial crops of cotton and sugar beet.

The Makhtaaral Region, which is the area considered in this research, is located in the South Kazakhstan near the border with Uzbekistan. Under the dry climate of the region, irrigation is needed to achieve acceptable agricultural production. The total irrigated area in this region is 32,500 hectares and much is threatened by a high watertable and salinity. Cotton accounts for about 70% of the cultivated area of South Kazakhstan. Seasonal precipitation and available water resources for irrigation together, have not been sufficient to meet the cotton water requirements since the early 1990s. In addition, irrigation with water of low quality, and poor leaching and drainage management as well as a shallow watertable, has increased the salt content in the soil root zone. As a result, the cotton yields reduced by about 40% due to water stress, salinity and waterlogging, during the 1990s. This in turn has resulted in a considerable decrease in net returns from crop production (Mott MacDonald, 1999).

Under the present conditions there are some areas in which plants are not under salinity stress since the soil salinity is still under the threshold value at which stress begins. Water stress has in fact been the main reason for declining yields. Salinity will, however, become a major problem in the near future (Mott MacDonald, 2004) if appropriate action is not taken now.

1.4 The WRMLIP Project

After the independence of Kazakhstan from the former Soviet Union, many state owned farms in South Kazakhstan, including the organisations that managed them, were privatised. There was no restructuring of these organisations or of the physical facilities of the agricultural system. This led to breakdown of the irrigation and drainage systems, damage to the environment and a significant reduction in agricultural production. As a result, the watertable rose to be in the rootzone causing salinity and waterlogging problems. ADB (1997) indicated that about 80% of the irrigated area was affected by salinity and water logging. During the 1990s, the main influence on crop yield was, however, water stress and not salinity.

Table 1.1: Land salinisation in Central Asia

Country	Irrigated Area (ha)	Area Affected by salinisation	
		ha	% of Irrigated Area
Kyrgyz Republic	1,077,100	124,300	11.5%
Tajikistan	719,200	115,000	16.0%
Kazakhstan	2,313,000	>763,290	>33.0%
Turkmenistan	1,744,100	1,672,592	95.9%
Usbekistan	4,280,600	2.140,550	50.1%
Central Asia in Total	10,134,000	4,815,732	47.5%

Source: Irrigation in Central Asia (Bucknall *et al.,* 2003)

Figure 1.1: Map of Kazakhstan

(http://www.go.hrw.com/atlas/norm_htm/kazakstn.htm)

Mott MacDonald, in association with Temelsu and Zher-Ana, carried out the WRMLIP project, which was funded by the Asian Development Bank (ADB) and the Government of Kazakhstan. The project area is a part of the major irrigated agricultural area of Golodnaya Steppe. Figure 1.2 shows the project location.

One of the project aims was to improve irrigation and drainage management and to increase agricultural productivity through maximising crop return per unit of water applied. In addition, the project also aimed to provide field and laboratory equipment and materials required for data collection as well as providing training for the staff of the organisations dealing with the agricultural system and tasked to take over management responsibilities of the irrigation and drainage systems.

1.4.1 Irrigation System

The water source for irrigation in Makhtaaral is the Syr Darya River, which flows from the Tien Shan Mountains in Kyrgyzstan. The length of the Syr Darya is 2,529 km. The last 1700 km are through Kazakhstan, where the river exhibits a strong meander pattern (EC, 1997). The water is diverted from Syr Darya River at the Farkhadskaya Hydroelectric complex in Uzbekistan by the 113 km long unlined Dostyk Canal, which has 73 km in Uzbekistan and 40 Km in Kazakhstan. The canal flow at the head is about 230 m^3/s with salinity of approximately 1100 mg/l. The canal flows into the Makhtaaral Region are controlled at a cross regulator near the Uzbekistan / Kazakhstan border. The canal was constructed in the 1950s and 1960s, and supplies irrigation water to a total command area of 205,600 hectares, 125,881 hectares of which is in Kazakhstan. Most of the WRMLIP project area lies on the Dostyk canal left bank (Mott MacDonald, 1999).

Generally, water supplies to the WRMLIP project area over the last ten years have been significantly lower than required, and insufficient to maintain a sustainable crop yield. The amounts of water delivered to the Makhtaaral Region between 1994 and 1997 decreased by about 50% (Table 1.2). Crops in many areas prior to the WRMLIP project depended on sub-irrigation from the high watertable (Mott MacDonald, 1999).

Table 1.2: Net irrigation deliveries to the Makhtaaral Region in the vegetation period in recent years

Year	Irrigated Area (ha)	Water Delivery $(Million\ m^3)$	Water Depth (m)
1993	43,545	168.5	0.39
1994	43,545	193.6	0.45
1995	43,468	159.0	0.37
1996	44,170	145.0	0.33
1997	43,642	87.4	0.20
1998	43,545	95.2	0.22

Source: Mott MacDonald (1999)

1.4.2 Drainage System

Drainage plays an important role in controlling watertable depth and helps avoid waterlogging and soil salinity problems. The topographic and hydrological conditions of South Kazakhstan require a good drainage system for sustainable crop production. Determination of the amount of drainage to be provided is important because it has a significant effect on the cost of crop production. The original drainage system installed in the 1950s consisted of horizontal or gravity-driven drains. It proved ineffective and failed to solve the problems of waterlogging and salinity because of inferior drainage tubing; poor management and drainage rates exceeding the design capacity of the system (ADB, 1997).

In the late 1970s, 800 Vertical Drainage Wells (VDW) and pumps were constructed to replace the original system. Drainage water is discharged to the Central Golodnaya Steppe Collector Drain, which transports water to the Arnasai depression in Uzbekistan, where it evaporates. This drainage system was used effectively until early 1990s. With the break-up of the former Soviet Union, privatisation, poor management and lack of funds, the physical conditions of the system deteriorated and by 1994 VDWs and pumps were no longer operational. As a result the watertable rose, and water logging and salinity became evident and resulted in reduced crop yield in many areas (Mott MacDonald, 1999).

1.4.3 Recent Irrigation Practices

Since the early 1990s water has been supplied mainly in winter (between January and March) from Farhadskaya Hydropower station, and used to apply leaching water to reduce soil salinity. Generally, the irrigation applications have been low since the early 1990s. Irrigation scheduling has been inappropriate, resulting in water stress during sensitive growth stages (flowering and yield formation), and water supplies from the Dostyk Canal have not been sufficient to meet crop water requirements. As a result, sub-irrigation from the shallow watertable by capillary flux has met a considerable part of the water requirements, but also increased the salinity level in the rootzone. Much of the leaching applications are thus subsequently used in sub-irrigation.

1.5 The Need for Mathematical Modelling

Key factors affecting sustainable crop production in arid and semi-arid regions are water availability over the different growth stages, soil salinity and waterlogging. What is required in managing water and soil salinity is a means of assessing how different irrigation and drainage practices affect potential crop yield, and long term sustainability. Advances in computer technology in recent decades have permitted improvements in mathematical modelling of crop, soil and climate systems. Vadose zone models can provide useful information about the impact of different irrigation and drainage practices. Many models have been developed and used to simulate water and solute flux in the crop rootzone (Vanclooster, *et al.,* 1994; Fernandez *et al.,* 2002; Simunek, *et al.,* 1996; Simunek, *et al.,* 1999; Droogers *et al.,* 2000; Wang *et al.,* 2001; Zhang and Dawes, 1998; Van Dam *et al.,* 1997; Van Dam, 2000; Smets *et al.,* 1997; Joshi *et al.,* 1995).

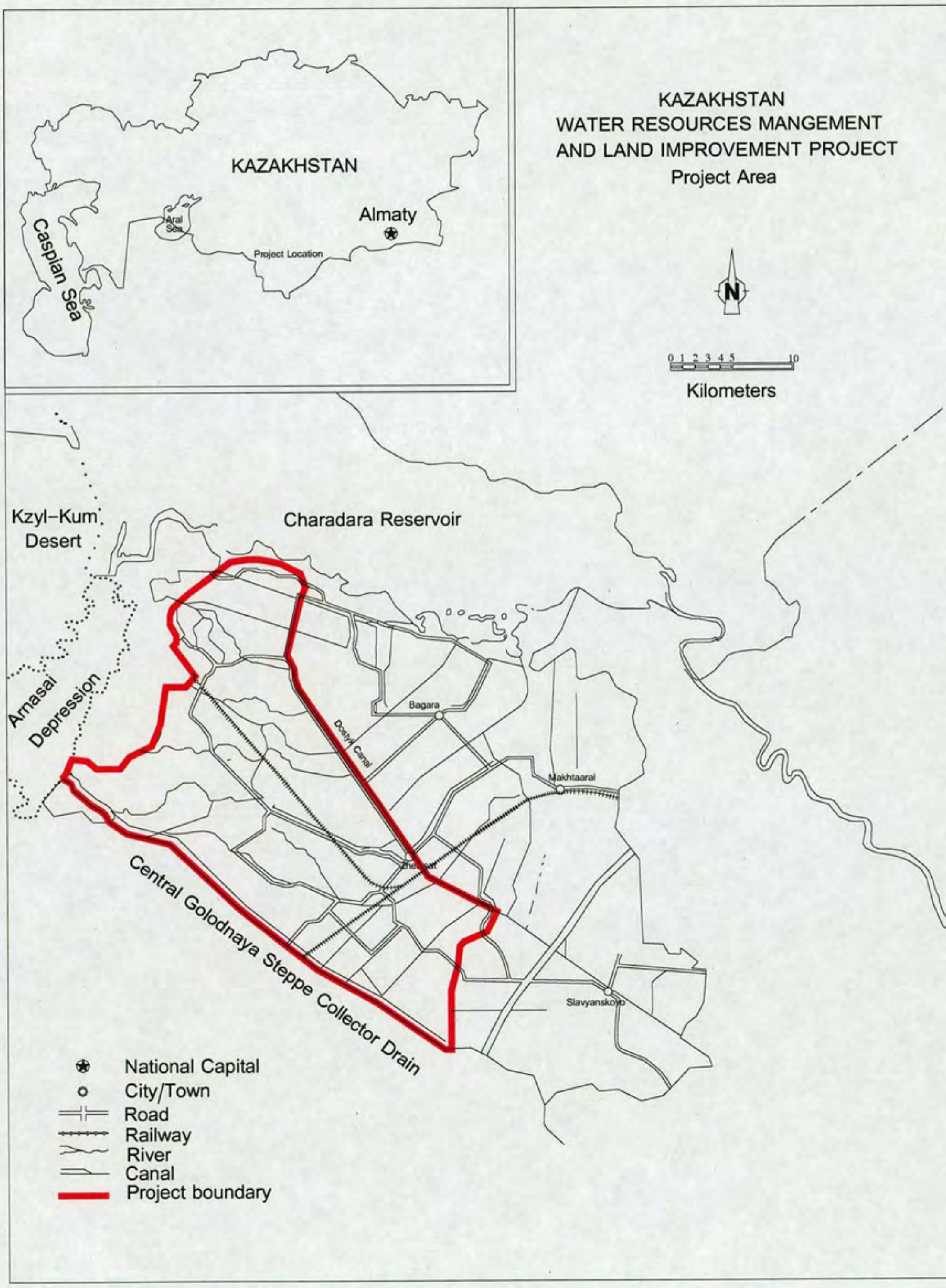


Figure 1.2: The WRMLIP Project location (ADB, 1997)

These models can deal with the interaction between the soil and crop and water management variables such as irrigation, leaching and drainage. They can be used to determine the most beneficial combinations between water management variables leading to sustainable crop production. Vadose zone models are increasingly being used to evaluate alternative management practices and subsequently to identify the most efficient management strategies for different sets of conditions (Querner *et al.,* 1997; Droogers and Kite, 2001; Droogers and Torabi, 2002; Kite and Droogers, 2000a; Qureshi *et al.,* 2002).

Most models are driven by a fundamental input of reference crop potential evapotranspiration. Actual crop evapotranspiration is generally controlled by available soil moisture. Crop yield in many models (Simunek *et al.,* 1996; Droogers *et al.,* 2000; Perez *et al.,* 2002; Qureshi *et al.,* 2002) is computed using one of a number of crop yield response functions (Stewart *et al.,* 1976; Jensen, 1968; Minhas *et al.,* 1974; Rao *et al.,* 1988; Doorenbos and Kassam, 1979; Martin *et al.,* 1984; de Wit, 1958). These can be used as a tool for evaluating the effect of alternative irrigation scheduling strategies, especially when water is a limited resource. These functions depend mainly on the calculation of crop evapotranspiration. Accordingly, estimation of crop yield requires precise functions as well as accurate procedures that consider most factors affecting crop transpiration such as water stress, salinity stress and waterlogging. Some of the mathematical models developed (Vanclooster *et al.,* 1996; Wang *et al.,* 2001; Joshi *et al.,* 1995;) use methods that predict crop transpiration assuming that the crop is only under the affect of soil water stress and do not consider reduction in transpiration and yield caused by other factors such as the affect of soil salinity stress. This limits applicability of these models under arid and semi-arid conditions where water shortage and salinity are the major problems. The combined effect of water and salinity stress should be considered when computing yield response.

Crop yield should be the primary criteria for evaluating alterative irrigation practices. However, many of the existing vadose zone water and solute transport models do not include yield response functions. For example, the WAVE model (Vanclooster, *et* *al.,* 1994) does not include a crop yield response function; although it calculates the time course of the leaf area index, the accumulation of the dry matter in the different plant parts, the root length and root density extension rate. In addition, some models use yield response functions that are unable to evaluate the cumulative affect of water stress during the different growth stages (Droogers *et al.,* 2000; Zhang and Dawes, 1998).

Developing mathematical models for predicting crop transpiration and yield under non-standard conditions during the different growth stages, taking into account the effect of both soil water and salinity stress in model calculations is an important research area. Such models can be used to systematically evaluate alternative irrigation management strategies where water shortage and salinity problems exist, and to identify strategies that maximise sustainable crop yield under water shortage and salinity conditions.

1.6 Motivation for Work

Water stress and salinity are at present significant threats to sustainable irrigated agriculture in many parts of the world. With continued rapid population growth, and increasing dependence on irrigated agriculture to maintain food security, it is essential that improved approaches to irrigation and drainage management be found. The problems recently experienced in South Kazakhstan serve to highlight the issues. Cotton yields were reduced by about 40% due to water and salinity stress over period of about 10 years following deterioration of irrigation and drainage management systems. This in turn resulted in considerable decrease in net incomes from crop production (ADB, 1997; Mott MacDonald, 1999). Sustainable irrigation and drainage management to maintain and improve crop production is one of the most significant needs in areas under the effects of water stress and salinity. For this reason, there is an urgent need to research robust and more efficient modelling approaches to improve assessment of crop yield associated with water and salinity stress.

1.7 Thesis Objectives

The main objective of this research was to develop improved models for evaluating the impact of water and salinity stress on crop yield, that will lead to better understanding of the key factors affecting sustainability in irrigated agriculture in arid and semi-arid areas. Specific objectives were as follows:

- to evaluate existing crop yield response to water functions, and to select and adapt the most suitable function for incorporation in a more comprehensive crop production model;

- to review Vadose zone modelling techniques and their application in water and salinity management for sustainable crop production;

- to develop for a modelling approach to investigate long-term salinity build up in the root zone and its effects on crop yield;

- to calibrate a vadose zone model and assess the sensitivity of salinity build up and crop yield, to physical soil characteristics and to different irrigation and drainage management practices:- irrigation water application, leaching amounts and drainage rates;

- to apply the developed modelling approach to the Makhtaaral region of South Kazakhstan to evaluate current irrigation and drainage practices and to identify efficient and sustainable irrigation and drainage strategies;

1.8 Thesis Contributions

A generic methodology has been developed for modelling irrigation water management under water shortage and salinity conditions. The developed approach leads to a computational procedure that is able to deal with the combined effects of water and salinity stress on crop transpiration and on crop yield.

The developed approach is applicable under arid and semi-arid conditions in a wide range of water stress and salinity situation. It permits development of a better understanding of the complex interactions between leaching and irrigation water applications, watertable position, rootzone salinity and crop yields. The model developed permits investigation of the contribution of the watertable in meeting crop water requirements by capillary rise as well as the impact of shallow water tables on the salinity build up in the rootzone.

The research contributes to the development of more efficient and economic irrigation water management strategies for Makhtaaral region of South Kazakhstan that maximise crop production per unit of water applied. Optimal irrigation and drainage scenarios have been identified, and the sensitivity of these to model parameterisation explored. These scenarios would achieve sustainable management for crop production through providing sufficient water to meet crop water requirements, while keeping soil salinity in the rootzone under control in the long-term. The scientific solution has been translated into a format that is easily understood and applicable by irrigators to achieve sustainable water resources management.

1.9 Thesis Organisation

This thesis is organised in 8 chapters and three appendices:

Chapter 2 of the thesis provides a review of the basic concepts of evapotranspiration estimation procedures, the most important crop-water relationships, and the effect of water and salinity stress on crop growth and yield.

Chapter 3 describes the assessment of existing yield response models and selection of the most appropriate for incorporating in a crop production model.

Chapter 4 provides a comprehensive technical review of existing variably unsaturated flow models. It includes model theories, and limitations, as well as reviews their applications by other researchers.

Chapter 5 presents the underlying theory behind the WAVE model, which was adopted and developed for this research. It discusses the model limitations and the modifications that have been made to improve the model performance in predicting the effects of water stress and salinity on crop transpiration and yield.

Chapter 6 describes the modified WAVE model (WAVE_MS) set-up and parameterisation. The model calibration process and results are also described. It also provides an evaluation of the calibration results and an assessment of the model performance and of its potential in establishing efficient water and drainage management strategies.

Chapter 7 describes the application of the developed modelling approach to the Makhtaaral Region of South Kazakhstan. The effect of different irrigation and drainage scenarios on crop yield have been simulated and evaluated.

Chapter 8 provides the conclusions of the research. The chapter presents the achievement of the research and outlines the limitations of the work carried out. Recommendations for further research in the application of the developed modelling approach to model irrigation and drainage management are also made.

CHAPTER 2

Literature Review

2.1 Introduction

Water shortage and salinity are major problems in arid and semi-arid areas, impacting on the sustainability of agricultural production. Most salinity problems result from inappropriate management practice, such as using low quality irrigation water, inadequate leaching, and poor drainage. These can lead to salt accumulation in the rootzone. This thesis describes the development and application of a mathematical modelling approach for irrigation and drainage management under water shortage and salinity conditions. Optimum irrigation, leaching and drainage management practice is the key to avoiding soil water and salinity stress and to establishing sustainable crop production.

Evapotranspiration is one of the most important hydrological processes and crop yield response is linked closely to it. Yield response functions are not, however, well defined, particularly in relation to stages of growth. The effects of salinity on crop yield are also important, as is the combined affect of water and salinity stress. This chapter discusses the most important crop yield to water relationships and presents a review of models describing the effects of water stress and salinity on transpiration and crop yield response.

Following this introduction, section 2.2 describes the evapotranspiration process, and outlines different computational procedures used under both standard and non-standard conditions. A review of existing crop water production functions and water use efficiency and irrigation scheduling are presented in section 2.3. Crop yield response to salinity is discussed in section 2.4. Finally section 2.5 provides the concluding remarks.

2.2 Evapotranspiration

2.2.1 Definition

Evapotranspiration is a collective term combining:

i) transpiration through which water is removed from the soil by plant roots; a small part of the removed water is used in the growing processes to build plant tissue and the greater part is converted to vapour within the plant leaf and released to the atmosphere through stomata;

ii) evaporation through which water is converted to vapour and removed to the atmosphere; the evaporating surface could be a soil surface, water surface, or leaf surface (Israelsen and Hansen, 1962).

In both the transpiration and evaporation processes, energy is required to convert water to vapour. Water vapour is removed from the evaporating surface or from the plant leaves due to the difference between the vapour pressure at the evaporating surface or inside the plant leaves and the atmosphere. Solar radiation, air temperature, air humidity and wind speed affect the efficiency of the evapotranspiration processes. Crop type, variety, growth stage, and shading percentage, are crop factors effecting evapotranspiration. Soil salinity, soil moisture, soil fertility, soil type, the absence or presence of diseases, soil ability to conduct water to the root zone, and cultivation practices are management and environmental factors affecting actual evapotranspiration (Allen *et al.*, 1998).

2.2.2 Reference Crop Evapotranspiration

Reference crop evapotranspiration (ET_o) is generally the basis of determining crop water requirements. Doorenbos and Pruitt (1977) defined reference crop evapotranspiration as "*the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall green cover of uniform height, actively growing, completely shading the ground and not short of water*". Different techniques have been developed to calculate ET_o with different climatic data availability.

According to Kite and Droogers (2000b) the most common methods used for the estimation of ET_o can be divided into three groups:

i) direct calculation of ET_o from climatic data using empirical equations;

ii) use of hydrological models;

iii) use of methods based on remote sensing techniques.

For most irrigation planning and management problems, ET_o is a primary data input, and it is computed from climatic data.

There are several empirical equations that are used for estimating ET_o from climatic data. The FAO Irrigation and Drainage Paper No. 24 (Doorenbos and Pruitt, 1977) presents four procedures for computing ET_o depending on the availability of the climatic data. These methods are; Penman, Radiation, Blaney-Criddle, and pan evaporation. The FAO expert consultation held in May 1990 in Rome (Smith *et al.*, 1992), considered the Penman-Monteith equation to provide the best standard method for calculating ET_o. The FAO Penman-Monteith equation for ET_o calculation (Smith *et al.*, 1992) is now the method most widely used by scientists and engineers worldwide (Chiew *et al.*, 1995). The Penman-Monteith equation requires daily measurements of maximum and minimum air temperature, maximum and minimum relative humidity, total wind run, and actual sunshine hours. It is improved if solar radiation data are available. Smith *et al.*, (1992) found that the Penman-Monteith equation gave ET_o values more closely related to lysimeter values than other methods. Following these results, Smith *et al.*, (1992), recommended that the Penman equation presented in the FAO Irrigation and Drainage Paper No. 24 be replaced by the FAO Penman-Monteith equation. This defines ET_o as "*the rate of evapotranspiration from a hypothetical crop with an assumed crop height (12 cm) and a fixed canopy resistance (70 s/m) and albedo (0.23) which would closely resemble evapotranspiration from an extensive surface of 8 to 15 cm tall, green cover of uniform height, actively growing, completely shading the ground and not short of water*". The FAO-24 report (Doorenbos and Pruitt, 1977) has now been updated by the FAO-56 report (Allen *et al.*, 1998) in which two methods have been described for calculating ET_o - FAO Penman-Monteith, and FAO pan evaporation. Chiew *et al.*, (1995) found that there was a satisfactory correlation between class-A pan evaporation and the Penman-Monteith equation. The Penman-Monteith equation has been applied successfully in many regions and under many conditions (Kashyap and Panda, 2001).

Under conditions where sufficient climatic data are not available for the Penman-Monteith method, alternative methods are available. The Hargreaves equation for example needs only maximum and minimum air temperature as inputs (Hargreaves *et al.*, 1985). However, this equation may require local calibration for acceptable performance. Gavilan *et al.,* (2006) calibrated the Hargreaves equation against Penman-Monteith FAO-56 (Allen *et al.,* 1998) for the Andalusian region of south Spain. They suggested that, the original coefficient (0.0023) be replaced by 0.0021 when the difference between maximum and minimum temperature for the day $\Delta T > 12\,^oC$ and the average wind velocity $V < 1.5\ m\ s^{-1}$ and by 0.0027 when $\Delta T < 12\,^oC$ and $V < 1.5\ m\ s^{-1}$.

2.2.3 Evapotranspiration under Non-standard Conditions

For accurate evapotranspiration estimation, the effect of non-standard management and environmental conditions must be taken into consideration. Allen *et al.*, (1998) defined evapotranspiration under non-standard conditions as "*the evapotranspiration from a crop grown under the effect of management and environmental conditions which are non-optimal*". They identified the following non-standard conditions:- soil salinity, water stress, waterlogging, soil type, soil fertility, the presence and absence of diseases, soil ability to conduct water to the root zone, and cultivation practices and management. Soil water stress and salinity are the factors most affecting transpiration. As a crop comes under stress, the transpiration rate decreases and falls below the potential transpiration rate. Evapotranspiration under non-standard conditions is usually estimated from reference crop evapotranspiration (ET_o), using a crop coefficient (K_C) and a crop stress factor (K_S). K_S accounts for the effect of non-standard conditions. The adjustment equations presented by Allen *et al.*, (1998) are:

$$ET_{c\,adj} = (K_S.K_{cb} + K_e)ET_o \qquad (2-1)$$

where, $ET_{c\,adj}$ adjusted crop evapotranspiration

K_S crop stress factor

K_{cb} basal crop coefficient

K_e soil evaporation coefficient

If a single crop coefficient is being used, then the equation is simply:

$$ET_{c\,adj} = (K_S K_C)ET_o \qquad (2-2)$$

George *et al.*, (2000) presented a very similar equation to estimate crop evapotranspiration under soil water stress conditions:

$$ET_{(i,j)} = ET_{o(i,j)}\left[K_{C(i,j)}K_{S(i,j)} + K_W\left(0.9 - K_{C(i,j)}\right)\right] \qquad (2-3)$$

where, K_W is a dimensionless ET reduction coefficient which has values of 0.8, 0.5, and 0.3 respectively, for the first, second, and third day following a rainfall or irrigation event and accounts for excessive evaporation from the bare soil surface at the beginning of the cropping season,

i is the time index (normally in days)

j is a spatial index.

2.2.4 Soil Water and Salinity Stress

Allen *et al.*, (1998) presented the following function for estimating K_S under soil water stress (when rootzone soil moisture depletion exceeds readily available water $D_r > RAW$):

$$K_S = \frac{TAW - D_r}{TAW - RAW} = \frac{TAW - D_r}{(1-p)TAW} \qquad (2-4)$$

where, K_S is the transpiration reduction factor (0-1),

D_r is the rootzone soil moisture depletion (mm),

TAW is the total available water (mm),

RAW is the readily available water in the rootzone (mm), which is the fraction of TAW that a crop can extract from the root zone without suffering water stress $(RAW = pTAW)$,

p is the fraction of total available soil moisture that can be depleted from the root zone before soil moisture stress.

George *et al.*, (2000) presented two methods used to estimate K_S, one based on a linear function and the other on a logarithmic function. The linear function was essentially that given by Allen *et al.*, (1998). The logarithmic function may be written as:

$$K_{S(i,j)} = \frac{\log\left[1 + 100\left(1 - \left(\left(\theta_{FC(j)} - \theta_{(i,j)}\right) / \left(\theta_{FC(j)} - \theta_{PWP(j)}\right)\right)\right)\right]}{\log[101]} \qquad (2-5)$$

What is missing from the logarithmic function is the concept of readily available moisture or a threshold below which stress begins.

Martin *et al.*, (1984) used a very similar approach to those outlined above to estimate the soil water stress coefficient:

$$K_S = 1; \quad \text{if} \quad E_W > 0.5 \qquad (2-6a)$$

$$K_S = \frac{E_W}{0.5}; \quad \text{if} \quad 0.0 \le E_W \le 0.5 \qquad (2-6b)$$

where, E_W is the fraction of extractable water remaining in the crop rootzone that can be written as

$$\frac{\left(\theta_{(i,j)} - \theta_{PWP(j)}\right)}{\left(\theta_{FC(i,j)} - \theta_{PWP(j)}\right)} \qquad (2-7)$$

where, $\theta_{(i,j)}$ is the soil moisture content on day i (m^3/m^3),

$\theta_{FC(j)}$ is the soil moisture content at field capacity (m^3/m^3),

$\theta_{PWP(j)}$ is the soil moisture content at permanent wilting point (m^3/m^3).

The above approaches to determining soil water stress are based on soil water balance approaches, and use the concepts of field capacity, permanent wilting point and readily available moisture.

The following equation can be used to calculate K_S under salinity stress (Allen *et al.*, 1998):

$$K_S = 1 - \frac{b}{K_y 100}\left(EC_e - EC_{ethreshold}\right) \qquad (2-8)$$

where, EC_e is the mean electrical conductivity of the saturation extract for the root zone $(dS\ m^{-1})$

$EC_{ethreshold}$ is the electrical conductivity of the saturation extract when yield starts to become affected by salinity

K_y is a yield response factor

b is the reduction in yield per increase in EC_e $(\%/(dS\ m^{-1}))$

For conditions when the crop is under both soil salinity stress ($EC_e > EC_{ethreshold}$), and soil water stress $D_r > RAW$, Allen *et al.*, (1998) recommended the following equation:

$$K_S = \left(1 - \frac{b}{K_y 100}\left(EC_e - EC_{ethreshold}\right)\right)\left(\frac{TAW - D_r}{(1-p)TAW}\right) \qquad (2-9)$$

2.2.5 Approaches for Use with Variably Saturated Flow Modelling

The approaches outlined above are suitable for use with standard water balance approaches to soil moisture modelling. With more sophisticated soil moisture modelling, using solutions of the Richards equation, it is possible to adopt transpiration reduction functions that are based on soil moisture tension or pressure head and the osmotic head of the soil water solution.

Homaee *et al.*, (2002a) described a transpiration reduction function proposed by Feddes *et al.*, (1978). This function depends only on the effect of soil water pressure head:

$$\alpha(h) = \frac{h - h_4}{h_3 - h_4} \qquad (2-10)$$

where, $\alpha(h)$ is a dimensionless transpiration reduction function of the soil water pressure head $(0 \le \alpha \le 1)$,

h is soil water pressure head,

h_3 is soil water pressure head at the threshold of moisture stress,

h_4 is soil water pressure head at wilting.

A recent review of transpiration reduction functions was provided by Homaee *et al.*, (2002b). They present a number of transpiration reduction functions that take into account the combined effect of water stress and salinity. They present additive functions (van Genuchten, 1987), multiplicative functions (van Genuchten, 1987; Dirksen *et al.*, 1993; Van Dam *et al.*, 1997; Homaee, 1999) and the conceptual combined method (Homaee, 1999). The additive function of van Genuchten (1987) is written as:

$$\alpha(h, h_o) = \frac{1}{1 + [(a_1 h + a_2 h_o)/h_{50}]^p} \qquad (2-11)$$

where, $\alpha(h, h_o)$ is a dimensionless reduction factor reflects the combined effect of water stress and salinity on crop transpiration,

h is soil water pressure head,

h_o is the soil solution osmotic head,

h_{50} is the value of soil water pressure head at which crop transpiration is reduced by 50%,

a_1 and a_2 are weighting factors of h and h_o respectively,

p is an empirical parameter.

The multiplicative reduction function proposed by Genuchten (1987) is written as:

$$\alpha(h,h_o)=\frac{1}{1+[h/h_{50}]^{p_1}}\times\frac{1}{1+[h_o/h_{o,50}]^{p_2}} \qquad (2-12)$$

where, p_1 and p_2 are empirical parameters.

Dirksen *et al.*, (1993) proposed the following reduction function:

$$\alpha(h,h_o)=\frac{1}{1+[(h^*-h)/(h^*-h_{50})]^{p_1}}\times\frac{1}{1+[(h_o^*-h_o)/(h_o^*-h_{o,50})]^{p_2}} \qquad (2-13)$$

where, h^* and h_o^* respectively are the soil water pressure head threshold and the osmotic pressure threshold values for stress.

Van Dam *et al.*, (1997) suggested the following function:

$$\alpha(h,h_o)=\frac{h-h_4}{h_3-h_4}\times\left[1-\frac{a}{360}(h_o^*-h_o)\right] \qquad (2-14)$$

Homaee (1999) proposed the following combined water stress and salinity function:

$$\alpha(h,h_o)=\frac{1}{1+((1-\alpha_{01})/\alpha_{01})[(h^*-h)/(h^*-h_{\max})]^{p_1}}$$
$$\times\frac{1}{1+((1-\alpha_{02})/\alpha_{02})[(h_o^*-h_o)/(h_o^*-h_{o,\max})]^{p_2}} \qquad (2-15)$$

where, $h_{\max}$ is the water pressure head at which the reduction factor reaches its minimum value,

$h_{o,\max}$ is the osmotic pressure head at which the reduction factor reaches its minimum value,

α_{01}	is the value of α corresponding to $h_{\max}$,
α_{02}	is the value of α corresponding to $h_{o,\max}$

Also Homaee (1999) presents the following function, which is a combination of the reduction function of Feddes *et al.*, (1978) with that of Maas and Hoffman (1977):

$$\alpha(h,h_o)=\frac{h-(h_4-h_o)}{h_3-(h_4-h_o)}\times\left[1-\frac{a}{360}(h_o^*-h_o)\right] \qquad (2-16)$$

The above functions require a great deal of parameterisation, and this does restrict their applicability.

2.3 Yield-water relationships

2.3.1 Water use efficiency

Water use efficiency is a useful indicator of crop productivity under limited water supply. Many variations have been noted in the literature in the definition of water use efficiency (*WUE*). Saranga *et al.*, (1999) defined *WUE* in agronomic terms as "*the ratio between total dry matter produced (or yield harvested) and the water used*" and in physiological terms as "*the ratio between the rate of carbon fixed and the rate of water transpired*". *WUE* can be defined as follows:

$$WUE=\frac{Y_a}{ET} \qquad (2-17)$$

where,	WUE	is water use efficiency in $kg/ha/mm$,
	Y_a	is the actual crop yield in Kg/ha,
	ET	is the seasonal water use or actual evapotranspiration in mm.

Irrigation water use efficiency $(IWUE)$ is defined as "*the ratio of the crop yield (ton ha^{-1}) to seasonal irrigation water applied including rain in (mm)*" (Al-Jamal *et al.*, 2001).

In arid and semi-arid areas, where water is scarce and population growth is high, improving *WUE* is very important for crop production and for efficient use of limited water resources. *WUE* can be increased by:

a) increasing yield without increasing the amount of water used;

b) maintaining yield and decreasing the amount of applied water (Howell and Hiler, 1975). This can be achieved by reducing the water application during specific stages of growth and minimising the loss of yield caused by water stress. The effect of water stress on yield is dependent on the stage of growth. There are many papers that address yield response issues.

In experiments in Turkey, Cakir (2004) evaluated the response of maize growth to water deficit in the different growth stages. Results showed that, tasselling and cob formation are the most sensitive stages during which all yield parameters were significantly affected by water stress. Results also showed that, even a short-duration water deficit during the rapid vegetative period, caused 28-32% reductions in the final dry matter weight of corn.

The most sensitive period to water stress for rice is during panicle development when water stress can severely reduce grain yield. However, water stress has only a small effect on grain yield when it occurs during the vegetative stage (Boonjung and Fukai, 1996). Dingkuhn *et al.*, (1996) reported that rice yield is highly sensitive to water deficit during reproductive development and grain filling. The most sensitive stage is flowering.

Champolivier and Merrien (1996) investigated the effect of water stress on oilseed rape yield in France. Yield was reduced by about 48% due to water stress when only 37% of the full water requirement was supplied to the plant from flowering to the end of seed set. Yield reduction was associated with the reduction in the number of seeds per plant.

Mastrorilli *et al.*, (1999) evaluated the sensitivity of the different growth stages of sweet sorghum to the same level of water stress. The least sensitive stage to water stress is the fast growing period. However, the authors found that irrigation should be applied in full in the early stages. An irrigation strategy based on the sensitivity of growth stages was established.

Zhang and Oweis (1999) reported that wheat yield response to water stress is more sensitive in the stem-elongation to grain-filling stage than in other stages. They suggested that the scarce water should be applied at these growth stages.

Mogensen *et al.*, (1985) found that drought sensitivity of wheat was greatest during tillering-shooting when the grain yield of only normal tillers was considered. Including the grain yield of both normal and late tillers, drought sensitivity was greatest during booting-heading stages.

Fabeiro *et al.*, (2001) found that for potatoes, the tuber bulking and ripening growing stages are the most sensitive to water stress. The absence of water stress in the ripening stage makes it possible to obtain a high percentage of medium and large tubers. They found that with total water application ranging between 520-570 mm (79%, 85-100%, 84-102%, and 80-100% of ET_C in establishment, vegetative growth, tuber bulking, and ripening stages respectively), a production rate of 40 ton/ha could be achieved when the tuber ripening stage is not affected by water stress.

Ayars *et al.*, (1999) reported significant yield and water-use efficiency increases in all crops when grown under subsurface drip irrigation in California. The use of high frequency irrigation resulted in reduced deep percolation. The increase in WUE was due to increased yield without increased water application.

It is clear that water stress affects crop yield and growth differently in different stages of growth, and that this sensitivity varies with crop type. To avoid reduction in crop yield caused by water stress, it is important to know which stage of crop growth is most sensitive to water stress and to apply irrigation water accordingly. It is also important to know the stages in which smaller amounts of water can be applied without any risk of yield reduction or with minimum yield reduction. There is no evidence in literature about the effect of the length of a stress period on crop yield.

2.3.2 Crop water production functions

The relationship between crop production and evapotranspiration is called the "*crop water production function*" and in effect it defines crop yield response to different levels of water applied. A crop water production function can be used to evaluate water use efficiency and to assist in effective allocation of water resources. Many crop water production functions have been developed and used to quantify crop yield response to water.

Jensen (1968) proposed a multiplicative function to determine the cumulative effect of water shortage in different stages of crop growth. The function used is of the form:

$$\frac{Y_a}{Y_m} = \prod_{i=1}^{n} \left(\frac{ET_a}{ET_m} \right)^{\lambda i} \qquad (2-18)$$

where, Y_a is the actual crop yield,

Y_m is the maximum or potential crop yield,

ET_a is the actual crop transpiration,

ET_m is the potential crop transpiration,

i is stage of growth,

λ_i is the crop sensitivity factor for growth stage i.

λ_i is an indicator for the effect of water stress on crop yield. The greater the value of λ_i the greater the effect of water shortage. A limitation of the Jensen function is in determining appropriate values of λ_i.

λ_i can be determined graphically (Tsakiris, 1982). For any particular growth stage:

$$\frac{Y_a}{Y_m} = \left(\frac{ET_{ai}}{ET_{mi}} \right)^{\lambda_i} \qquad (2-19)$$

and in logarithmic space:

$$\log\frac{Y_a}{Y_m} = \lambda_i \log\left(\frac{ET_{ai}}{ET_{mi}}\right) \qquad (2-20)$$

The problem with this method is in determining relative yield in different growing stages. Actual yield is not known until harvest. Tsakiris (1982) used relative yield values at different growth stages under different evapotranspiration deficits presented in the FAO Irrigation and Drainage Paper No. 33 (Doorenbos and Kassam, 1979) to permit calculation of values of λ_i. λ_i was thus conditioned entirely on the Doorenbos and Kassam (1979) data, the origins of which are unclear.

Doorenbos and Kassam (1979) suggested that the following function be used to determine the crop yield response to water through various stages of crop growth:

$$\left(1-\frac{Y_a}{Y_m}\right) = K_y\left(1-\frac{ET_a}{ET_m}\right) \qquad (2-21)$$

where, K_y is the yield response factor depending upon the crop and the stage of crop growth. However, no guidance is given by Doorenbos and Kassam on how to apply the yield response function when water shortage occurs cumulatively during different stages of crop growth (Wardlaw and Barnes, 1996; Rao *et al.*, 1988). Values for K_y are published by Doorenbos and Kassam for many crop types to determine the yield reduction over the whole growing season and for individual growth stages. Al-Jamal *et al.*, (2000) determined K_y values from field experiment. He determined a K_y value of 1.52 for onion, which is similar to that 1.5, obtained by Doorenbos and Kassam, (1979) for onion stressed only at the yield formation period.

Rao *et al.*, (1988) used the same procedure as Tsakiris to calculated λ_i for each value of K_y listed by Doorenbos and Kassam (1979). Values of λ_i corresponding to different values of K_y are presented in Table 2.1.

Table 2.1: Values of λ_i corresponding to different values of K_y

K_y	0.20	0.25	0.30	0.40	0.45	0.50	0.55	0.60	0.75	0.80	1.00	1.50
λ_i	0.15	0.19	0.24	0.32	0.37	0.42	0.47	0.52	0.68	0.74	1.00	1.95

Source: Rao *et al.*, (1988)

Zhang and Oweis (1999) used the Jensen function to investigate the effect of water deficit during certain growth stages on wheat yield in Tel Hadya in northern Syria. Non-linear regression procedures were used to find λ_i. They found that crop yield increased linearly by 160 $Kg.ha^{-1}$ for bread wheat and 116 $Kg.ha^{-1}$ for durum wheat per 10 mm increase in evapotranspiration above a threshold of 200 mm. The sensitivity index λ_i values for wheat at the different growing stages are presented in Table 2.2.

Table 2.2: Sensitivity index (λ) of bread wheat and durum wheat to water stress at different growing stages at Tel Hadya in Syria

Crop	Seedling	Stem elongation-booting	Booting - anthesis	Anthesis-soft dough	Soft dough-maturity
Bread wheat	0.01	0.31	0.28	0.21	0.10
Durum wheat	0.15	0.31	0.17	0.26	0.07

Source: Zhang and Oweis, (1999)

Minhas *et al.*, (1974) proposed the following multiplicative type function:

$$\frac{Y_a}{Y_m} = \prod_{i=1}^{n}\left[1-\left(1-\frac{ET_a}{ET_m}\right)_i^2\right]^{b_i} \qquad (2-22)$$

where, b_i is the sensitivity factor for growth stage i. b_i can also be derived using relative yield values at different growth stages under different evapotranspiration deficits presented in Doorenbos and Kassam (1979).

Stewart *et al.*, (1976) proposed the following additive function:

$$\frac{Y_a}{Y_m} = 1 - \sum_{i=1}^{n} K_y \left(1 - \frac{ET_a}{ET_m}\right)_i \qquad (2-23)$$

This function uses the same K_y as published in the FAO Irrigation and drainage Paper No. 33 by Doorenbos and Kassam, (1979). Wardlaw and Barnes (1996) questioned the applicability of the function, demonstrating that the Stewart function indicated almost total yield loss with 20% and 15% reduction in the actual evapotranspiration of rice and dry foot crops respectively.

Martin *et al.*, (1984) suggested the following function for grain sorghum, wheat and soybean, which can be used to predict the relative yield of these crops:

$$\frac{Y_a}{Y_m} = (1 - b_e) + b_e \left(\frac{ET_a}{ET_m}\right) \qquad (2-24)$$

where, b_e is an empirical seasonal yield coefficient.

Values for b_e are summarized by Martin *et al.*, (1984) for grain sorghum, soybean and hard red winter wheat only. Lamsal *et al.*, (1999) derived an experimental value of b_e for wheat:

$$Y_a / Y_m = 1 - 1.07 + 1.07(ET_a / ET_m) \qquad (2-25)$$

A further multiplicative function was proposed by Rao *et al.*, (1988):

$$\frac{Y_a}{Y_m} = \prod_{i=1}^{n} \left[1 - K_y \left(1 - \frac{ET_a}{ET_m}\right)_i\right] \qquad (2-26)$$

The function is similar to that proposed by Minhas *et al.*, (1974), but is intended to be used with the crop yield response factors published by Doorenbos and Kassam. In assessment of crop yield response functions, Wardlaw and Barnes (1996) suggested that Rao function was at that time the best approach to crop yield response modelling. Results from the Jensen function (Jensen, 1968) were similar but parameterisation of the sensitivity factor is not as well defined as for the Rao function.

Rao *et al.*, (1988) compared the relative yield of cotton, groundnut, maize, sorghum, sunflower, and wheat predicted by different crop water production functions (Jensen 1968; Stewart *et al.*, 1976; and Rao *et al.*, 1988) against field data. They concluded that, although all three functions predicted identical values of relative yield at lower levels of soil moisture stress, the Stewart function gives very low relative yield values (sometimes negative) when using higher values of K_y even when the relative evapotranspiration deficit at any stage of growth does not exceed 50%.

Rao *et al.* (1988) also compared the crop yield predicted by different crop production functions with field data collected by several researchers (Hall and Butcher, 1968; Jensen, 1968; Hiler and Clark 1971; Hanks 1974; Minhas *et al.*, 1974; Blank, 1975; Stewart *et al.*, 1976; Sudar *et al.*, 1981). They reported that the parameters for many functions need to be determined locally. Their conclusion was that functions are valid under the conditions where they were developed.

2.3.3 Irrigation scheduling

Under water shortage conditions, efficient, reliable, and economical use of limited water resources is important. In modern agriculture, this can be achieved through irrigation scheduling, taking into account soil, crop, and climate factors and their interactions. Information on soil moisture status, crop evapotranspiration, and rainfall are required to improve irrigation scheduling strategies, make efficient use of the limited water resources, and to increase returns (Botes *et al.*, 1996).

In general, irrigation scheduling is defined as "*determining when to irrigate and how much water to apply*" or as "*deciding when to start and when to stop an irrigation*" (Martin *et al.*, 1992). If water is limited, irrigation should be scheduled to maximise crop production per unit of water applied. In areas where land is more expensive than water, irrigation should be scheduled to maximise crop production per unit of planted area (FAO, 1973).

According to Hill (1991), irrigation scheduling methods are based on three approaches:- crop monitoring, soil monitoring, and water balance techniques. For the method based on crop monitoring, leaf water potential and canopy temperature are used to decide when to irrigate. The disadvantage of this method is that the irrigation decision is made after the plant has suffered stress, and this may affect the crop yield. Soil moisture monitoring can be effectively used for irrigation scheduling purposes. The disadvantage of this method is that it is time consuming and can be expensive. Water balance techniques use soil water budgeting over the root zone. This can be done by hand calculations or by using computer models.

Many models have been developed and become widely accepted and used by irrigators. CROPWAT is a computer programme initially developed by Smith, (1992). This model uses the Penman-Monteith equation to calculate the crop water requirements from climatic data. It can be used for scheduling irrigation under different management conditions. The CROPWAT 7 package (Clarke *et al.*, 2000) is accompanied by a comprehensive climatic database.

George *et al.*, (2000) developed a model called ISM (Irrigation Scheduling Model) to schedule irrigation under various management options. The model consists of soil water balance and crop yield sub-models. It uses climatological, crop, and soil data as inputs, and uses the crop water production function suggested by Martin *et al.*, (1984) to predict crop yield. The ISM model was tested by George *et al.*, (2000) against field data and CROPWAT. They found that ISM and CROPWAT gave similar values of soil moisture, although they showed some variation after the second irrigation. The ISM was verified with experimental data for a bean crop. Simulated bean yield was slightly higher than observed yield. They considered that use of the ISM can improve irrigation water use efficiency.

Raghuwanshi and Wallender, (1998) developed a seasonal furrow irrigation model. The model includes soil moisture, irrigation hydraulics and economic optimisation components. A water balance equation is used to determined daily soil moisture depletion in an irrigated field. The model uses a systematic simulation technique to optimise furrow irrigation schedules and designs that minimise irrigation cost (maximise net return to water) by optimising inflow rate and cut-off time (minimising irrigation losses).

OPTIMEC is a computer model developed by Montesinos *et al.*, (2001). It includes four components:- a soil moisture model, an irrigation hydraulics model, a crop model, and an economic optimisation module. The model uses the multiplicative production function proposed by Rao *et al.* (1988). In the soil moisture model, daily levels of soil moisture are computed using a water balance equation. The economic optimisation module uses a genetic algorithm (GA) to find the optimum combination between the irrigation date, time of cut-off and inflow rate that maximises net profit. The model can be applied to any furrow irrigated field crop under different climatological and soil conditions. For a set of climatological, soil, furrow geometry, and crop data for sloping and blocked end furrows, OPTIMEC determines the optimum cropping calendar and irrigation schedule based on economic profit maximisation.

EPIC (**E**rosion **P**roductivity **I**mpact **C**alculator) is a crop simulation model used to optimise irrigation schedules for sunflower in Southern Italy. It uses 66 scenarios of irrigation times, seasonal irrigation amount and irrigation frequency. The model can be a useful tool for evaluating different irrigation management strategies (Rinaldi, 2001).

Ragab *et al.,* (2005) developed the SALTMED model for simulating water and solute transport, evapotranspiration and crop water uptake. The model can be used to examine the effect of irrigation water application, soil type, water quality on soil moisture and salinity distribution, leaching requirements and crop yield. The model can be used to manage irrigation, crop and soil in an effective way in order to save water and protect the environment.

2.3.4 Effect of irrigation scheduling on yield and water use efficiency

Appropriate irrigation scheduling means applying adequate amounts of irrigation water to a plant at the right times to avoid physiological water stress at critical growth stages.

Kang *et al.*, (2001) found that evapotranspiration, water-use efficiency (WUE), and harvest index (HI) for wheat depended on the controlled ranges of soil water content. Grain yield response to irrigation varied considerably with differences in soil moisture contents and irrigation scheduling. ET was largest with high soil water content, but this did not produce the highest yield and WUE was relatively low. High values of grain yield, WUE, and HI were produced under conditions of mild water deficit at the seedling and start of re-growth to stem-elongation stages, and with a further soil water depletion at the maturity to harvest stage. They suggest that periods of mild soil water depletion in the early vegetative growth period together with severe soil water depletion in the maturity stage is optimal for a limited irrigation regime.

Yazar *et al.*, (2001) evaluated the yield response of cotton to different irrigation applications using low-energy precision application $(LEPA)$ and trickle-irrigation in Southern Anatolia in Turkey. The effects of four different levels of irrigation (100, 75, 50, and 25% of cumulative Class-A pan evaporation on a 6-day basis) were investigated for $LEPA$. Two irrigation intervals (3-day and 6-day) and three different levels of irrigation (100, 67, and 33% of cumulative Class-A pan evaporation) were investigated for the trickle system. It was found that highest average seed cotton yield of $5850\,Kg/ha$ was obtained from the full-irrigation treatments (814 $mm/season$) in trickle-irrigated plots with 6-day intervals. However there was no significant difference between 100% and 67% irrigation levels under trickle irrigation. The highest yield in $LEPA$ plots was obtained with the full irrigation treatments (814 $mm/season$) and was 4750 Kg/ha. Maximum $IWUE$

and WUE were found as 0.813 Kg/m^3 and 0.714 Kg/m^3 in trickle-irrigation with 67% irrigation on a 6-day interval.

Cetin and Bilget (2002) also investigated cotton irrigation in Southern Anatolia in Turkey. They found cotton yields (lint + seed) under furrow irrigation of 3630 kg/ha. WUE was 3.87 $Kg/ha/mm$. Increasing the amount of water applied resulted in a higher yields up to applications of 1400 mm, but thereafter yield declined again.

Al-Jamal *et al.*, (2001) compared water-use efficiency for sprinkler, furrow, and subsurface drip irrigation methods for an onion crop in Southern New Mexico. They found that $IWUE$ using sprinkler irrigation was higher than that with subsurface drip and furrow irrigation methods. WUE cannot be improved by letting onions suffer from water stress.

The effect of irrigation scheduling on crop yield and net benefit in the Loma de Quinto Irrigation District in Spain was evaluated by Dechmi *et al.* (2003) using the CROPWAT model. Simulation results identified water stress caused by deficit irrigation and/or large irrigation intervals. Water stress resulted in alfalfa yield reductions of 10-17%. The optimum irrigation scheduling that avoided yield reduction involved applying light and frequent irrigation.

Sezen and Yazar (2006) studied the effect of limited irrigation on wheat yield and water use efficiency in the arid Southeast Anatolia region of Turkey. Results show that severe soil water deficit significantly reduced crop transpiration, grain yield, water use efficiency and harvest index. The highest average grain yield of 8340 Kg/ha was obtained under full irrigation water application. The highest average WUE ranged between 12.6 to 14.9 $Kg/ha/mm$. However, under water shortage, less than full irrigation can produce acceptable yields and high water use efficiency. Improving water productivity can contribute to water savings.

Sezen *et al.,* (2006) examined the effect of different irrigation regimes on the yield and water use of bell pepper in the Mediterranean region of Turkey. The highest yields of 33,140 Kg/ha in the 2002 growing season and 35,300 Kg/ha in the 2003 growing season were obtained with irrigation applied using 3-6 days irrigation intervals. Water use efficiency WUE ranged from 4.7 to 7.6 Kg/m^3 in the 2002 growing season and ranged from 6.4 Kg/m^3 to 7.9 Kg/m^3 in the 2003 growing season. Irrigation interval significantly influenced peppers yield and WUE in both years.

With a limited water resource, an effective irrigation scheduling strategy that ensures applying the right amount of water at the right time is important to overcome problems of soil water stress, soil salinity and irrigation water loss by evaporation and deep percolation. Developing such a strategy is complicated because it depends on soil, crop and climatic factors and their interaction. Yield and water use efficiency can be the best indicators for strategy evaluation. Although, crop water production functions have been extensively used to quantify yield response to water supply, the impact of accumulated stress on potential evapotranspiration may not be adequately described.

2.4 Salinity affect

2.4.1 Introduction

Soil salinity is a major problem in the development of irrigated agriculture in many arid and semi-arid regions of the world. About 50% of the irrigated area of the world is affected by salinity or has the potential to be affected in the future (Tyagi, 1986). In these regions of low precipitation and high potential evapotranspiration, salts can accumulate in the root zone if there is inadequate drainage, inadequate leaching, or a combination of these. Salt accumulation in the root zone is often caused by irrigation with poor quality water or by the upward movement of saline water from a shallow water table. Salts concentrate in the root zone as a result of the evapotranspiration process. Table 2.3 shows a classification of waters of different origins (Rhoades *et al.*, 1992).

The most important factors affecting salinisation are soil physical and chemical properties, water management practices, topography, quality of the irrigation water, depth to water table, shallow ground water quality, gypseous status of soils and climatic conditions (Lamsal *et al.*, 1999).

Salinity is a major cause of low crop yields and poor crop quality. Optimal crop yields can be obtained if the salinity of the soil solution does not exceed a certain threshold, which varies with crop type and variety. An increase in salinity above this threshold results in a decrease in yield. Table 2.4 shows salt tolerance level for various fruit crops (Ayers and Westcot, 1985). Where salinity is a problem, irrigation should meet both the crop water requirements and leaching requirements. Leaching means applying more water than the crop requires to leach out accumulated salts in the root zone. Leaching has been defined as "*the minimal fraction of the total water applied that must pass through the root zone to prevent reductions in crop yield below the acceptance level*" (Minhas, 1996). Leaching applications may be restricted by water shortage or by inadequate drainage.

2.4.2 The effect of salinity on crop transpiration and yield.

Soluble salts affect crop transpiration and yield in different ways:

(i) particular ions may be toxic to the crop;

(ii) the presence of salts makes it more difficult for plant root systems to remove moisture from the soil; salts have an affinity for water, and with salts present a plant must expend greater energy to extract water;

(iii) high levels of sodium and chloride cause nutrient deficiencies, especially calcium deficiency, which reduce plant growth;

(iv) the presence of salts reduces transpiration by reducing ground cover and sometimes due to partial stomatal closure (Allen *et al.*, 1998).

Table 2.3: Classification of waters

Type of water	EC (dS/m)	TDS (g/l)	Water class
Drinking and irrigation water	< 0.7	<0.5	None saline
Irrigation water	0.7-2.0	0.5-1.5	Slightly saline
Primary drainage water and groundwater	2.0-10.0	1.5-7.0	Moderately Saline
Secondary drainage water and groundwater	10.0-20.5	7.0-15.0	Highly saline
Very saline groundwater	20.0-45.0	15.0-35.0	Very highly saline
Sea water	>45.0	>35.0	Brine

Source: Rhoades *et al.*, (1992)

Table 2.4: Salt tolerance level for fruit crops

Crop	100% Yield		90% Yield		75% yield		50% Yield		Max
	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e
Almond	1.5	1.0	2.0	1.4	2.8	1.9	4.1	2.7	7.0
Apple, Pear	1.7	1.0	2.3	1.6	3.3	2.2	4.8	3.2	8.0
Apricot	1.6	1.1	2.0	1.3	2.6	1.8	3.7	2.5	6.0
Avocado	1.3	0.9	1.8	1.2	2.5	1.7	3.7	2.4	6.0
Date palm	4.0	2.7	6.8	4.5	10.9	7.3	17.9	12.0	32.0
Fig, Olive	2.7	1.8	3.8	2.6	5.5	3.7	8.4	5.6	14.0
Grape	1.5	1.0	2.5	1.7	4.1	2.7	6.7	4.5	12.0
Grapefruit	1.8	1.2	2.4	1.6	3.4	2.2	4.9	3.3	8.0
Lemon	1.7	1.1	2.3	1.6	3.3	2.2	4.8	3.2	8.0
Orange	1.7	1.1	2.3	1.6	3.2	2.2	4.8	3.2	8.0
Peach	1.7	1.1	2.2	1.4	2.9	1.9	4.1	2.7	7.0
Strawberry	1.0	0.7	1.3	0.9	1.8	1.2	2.7	1.7	4.0

Source: Ayers and Westcot, (1985)

EC_e - electrical conductivity of a saturated soil extract $(dS\ m^{-1})$

EC_w - electrical conductivity of the irrigation water $(dS\ m^{-1})$

FAO Irrigation and Drainage Paper No. 56 (Allen *et al.*, 1998) describes an approach for predicting crop yield as a function of soil salinity that is the same as that given in the FAO Irrigation and Drainage Paper No. 29 (Ayers and Westcot, 1985). Under standard conditions, crop yield remains at potential levels until a specific threshold electrical conductivity (EC_e) of the saturated soil extract is reached. Crop yield linearly decreases as the EC_e value increases above the threshold soil electrical conductivity. The relationship between crop yield and salinity can be written as:

$$\frac{Y_a}{Y_m} = 1 - \left[EC_e - EC_{ethreshold}\right]\frac{b}{100} \qquad (2-27)$$

where, Y_a is the actual crop yield,

Y_m is the potential crop yield when $EC_e < EC_{e\ threshold}$,

EC_e is the mean electrical conductivity of the saturation extract for the root zone $(dS.m^{-1})$,

$EC_{ethreshold}$ is the electrical EC_e at which crop yield first reduces below Y_m $(dS.m^{-1})$,

b is the reduction in yield per increase in EC_e $(\%/dS.m^{-1})$.

Values for $EC_{e\ threshold}$ and b are presented in FAO Irrigation and Drainage Paper No. 56 (Allen *et al.*, 1998) for many crops.

In an experiment to quantify the effect of salinity levels on tomato transpiration, yield and water use efficiency in Ankara, Turkey. Yurtseven *et al.,* (2005) reported that, crop transpiration, crop yield and water use efficiency significantly decreased with increasing salinity level in the soil rootzone. The decrease in these parameters started at 2.5 $dS\ \ m^{-1}$. The average decrease in yield caused by an increase in salinity from 2.5 $dS\ \ m^{-1}$ to 5.0 $dS\ \ m^{-1}$ was about 37%. As the salinity increased to 10.0 $dS\ \ m^{-1}$ a further reduction in yield of about 60% resulted.

Atis (2004) estimated the economic impact of soil salinity and waterlogging on cotton yield in the Gediz Delta in Turkey where salinity and waterlogging are the major cause for cotton yield reduction. Cotton yields were reduced by 34.4% and gross margin are reduced by $\$860/ha$ as a result of soil salinity and waterlogging.

In field experiments in the Jordan Valley, Abu-Awwad (2001) found that increasing irrigation water salinity by 3.7 times increased the salt concentration in the root zone by about 3.8-4.1 times and subsequently reduced fruit yield from lemon trees.

Lamsal *et al.*, (1999) studied the effect of soil salinity on evapotranspiration as well as on crop yield. It was found that as the soil salinity level increases, soil water availability decreases. Actual wheat transpiration and yields were significantly lower than their calculated potential values in saline soils, but very similar in the case of non-saline soils. According to these results, relationships between salt concentration and yield were established:

$$Y_a / Y_m = 1.009 - 0.02EC_e \qquad (2-28)$$

Cuartero and Fernandez-Munoz (1999) reported that tomatoes began to lose yield when irrigated with saline water of EC above $2-3\ dS\ m^{-1}$. 50% yield reduction occurred with moderately saline water of $9\ dS\ m^{-1}$. This reduction was mainly due to reduction in average fruit weight.

Vulkan-Levy *et al.*, (1998) studied the effect of irrigation quantity and its salinity on cotton yield in the northwest of the Negev. The irrigation water salinity ranged from 2 to 7.5 $dS\ m^{-1}$ and the seasonal water application ranged from 300 to 680 mm. They found that the maximum cotton yield (about $5000\,Kg/ha$) could be obtained with a water application of 500 mm (42% of class-A pan evaporation) and water salinity between 4 to 5 $dS\ m^{-1}$. Irrigation water salinity caused a reduction in the cotton yield and the salinity threshold increased with increasing water application. The following relationships between cotton yield and irrigation application were established:

$$Y = -2324.9 + 249I - 2.1I^2 \quad \text{for irrigation water salinity of } (2.0\ dS\ m^{-1}) \qquad (2-29)$$

$$Y = 468.7 + 61.2I \quad \text{for irrigation water salinity of } (7.5\ dS\ m^{-1}) \qquad (2-30)$$

where, Y is cotton yield $(kg\ ha^{-1})$,

I is irrigation water depth (cm).

A lysimeter experiment was conducted by Hutmacher *et al.* (1996) to determine the influence of shallow groundwater salinity on cotton water uptake in California. They reported that ground water contributed about 30 to 42% of seasonal total evapotranspiration with groundwater salinity $\leq 20\ dS\ m^{-1}$ but that this declined to 12-19% of total evapotranspiration at higher salinity levels.

Zhang *et al.*, (1999) also used a lysimeter to investigate capillary flux from a shallow water table and associated processes such as salt accumulation, plant water use, and growth response of lucerne. The results showed declines of 36% in transpiration, 42% in leaf area growth, and 67% in upward flux after salinity of the water table was increased from 0.1 to 16 $dS\ m^{-1}$. These results were compared against those obtained through a simulation using the WAVES model (Zhang and Dawes, 1998). The model is discussed in details in Chapter 4.

In an experiment to quantify crop growth, yield and water use of safflower under different combinations of soil and irrigation water salinity in California, Bassil and Kaffka (2002) found that increasing root zone salinity decreased root growth, water use, safflower biomass and daily and seasonal evapotranspiration. Reduced water use increased drainage in salt-affected root zones for the same irrigation amount. Safflower seed yield was not significantly influenced by soil or irrigation salinity. They suggested that saline water can be used to irrigate safflower without yield loss if the soil water salinity (EC_e) was less than 8 $dS\ m^{-1}$.

De Pascale and Barbieri (1997) evaluated the salt tolerance of broadbean using two models:

i) the Maas-Hoffman model (Maas and Hoffman, 1977; Ayers and Westcot, 1985; Allen *et al.*, 1998):

$$Yr = 100 - S(EC_e - T) \qquad (2-31)$$

ii) the van Genuchten model (van Genuchten, 1983):

$$Yr = 100 / \left[1 + \left(EC_e / EC_{e50}\right)^P\right] \qquad (2-32)$$

where: Yr relative yield;

T the salinity threshold expressed in $dS\ m^{-1}$;

S the slope of the relative yield – salinity relationship ($\% / dS\ m^{-1}$);

EC_e relates to the 0-60 cm soil layer;

EC_{e50} is the EC_e value at which Yr is 50%;

P is an empirical constant.

They found that, using the Maas-Hoffman model, the threshold value was 1.7 $dS\ m^{-1}$ and yield was reduced at the rate of 15% per $dS\ m^{-1}$, the salinity level at 50% yield reduction EC_{e50} was 5 $dS\ m^{-1}$, compared to 4.7 $dS\ m^{-1}$ found with the van Genuchten model.

De Pascale and Barbieri (1997) studied the effect of soil salinity on growth and yield of broadbean in Naples, Italy. They found that with an EC_e between 2 $dS\ m^{-1}$ and 6 $dS\ m^{-1}$, plant height was reduced by 60%, leaf area by 70%, dry matter by 45%, mean pod weight by 15% and the number of pods per plant by 48%. Higher salinity decreased the seed yield by 67% (reduction in weight and number of seeds). The following relationships between broadbean yield and soil salinity were established using Maas-Hoffman and van Genuchten models:

Maas-Hoffman model $$Y = 100 - 15.075(EC_e - 1.727) \quad (2-33)$$

Van Genuchten model $$Y = 100 / \left[1 + (EC_e / 4.704)^{3.011}\right] \quad (2-34)$$

Katerji *et al.*, (2001) studied the sensitivity of lentil to different levels of irrigation water salinity. The results showed that salinity affected the germination and survival of the seedling, the pre-dawn leaf water potential and maximum osmotic adjustment, the development of leaf area, dry matter and number of flowers, and finally, the yield. At an EC of 2 $dS\ m^{-1}$, the limit between non-saline and slightly saline soils, the yield reduction was about 20% and at an EC of 3 $dS\ m^{-1}$ it was 90-100%. According to these results the crop is highly salt sensitive and can be only grown on non-saline soils.

Katerji *et al.*, (2000) compared the tolerance of eight crops to salinity using a lysimeter experiment. Salinity significantly affected yield, evapotranspiration, pre-dawn leaf water potential and stomatal conductance. From these results the crops were classified according to their salt tolerance: sugarbeet and durum wheat as salt tolerant; broadbean, maize, potato, sunflower, and tomato as moderately salt sensitive. There are differences between these results and what published in the FAO Irrigation and Drainage paper No. 56. They attribute these differences to plant variety and weather.

Sharma and Rao (1998) reported the results of field experiments conducted for 7 years in which wheat was irrigated using drainage water of different salinity levels (EC_w 6, 9, 12, and 18.8 $dS\ m^{-1}$) during the dry winter season in India. They found that the yield reduction at different EC_w was 4.2% at 6 $dS\ m^{-1}$, 9.7% at 9 $dS\ m^{-1}$, 16.3% at 12 $dS\ m^{-1}$, and 22.2% at 18.8 $dS\ m^{-1}$. The following relationship between wheat yield and irrigation water salinity was obtained:

Relative grain yield $$RY_g = 100 - 1.82(EC_w - 4.0) \quad (2-35)$$

This relationship indicates that high salinity water up to 9 $dS\ m^{-1}$ can still provide 90% wheat yield in soils provided with subsurface drainage system.

Hussain *et al.*, (1997) found in Saudi Arabia that irrigation water with an EC of 13.40 $dS\ m^{-1}$ and above reduced barely germination and green matter production significantly. They concluded that a reasonable barley production in terms of green matter and dry matter could be obtained with irrigation water with an EC up to 9.26 $dS\ m^{-1}$ provided 15% excess water was applied as a leaching requirement. It was found that any further increase in irrigation water salinity could reduce the yield by up to 50% or more.

2.4.3 Irrigation water management for salinity control

Irrigation and drainage are key controls on rootzone salinity and its effect on agricultural production in arid and semi-arid areas. Khosla and Gupta (1997) evaluated the response of wheat to different depths of irrigation, and to drainage conditions using a lysimeter. The results showed that the growth and yield of wheat irrigated with saline water was affected to a greater extent in the undrained lysimeter than the drained lysimeter due to the rise in water table depth during the irrigation cycle. A higher grain yield was obtained with an increased depth of irrigation under drained conditions. In the undrained lysimeter the yield tended to be higher with smaller depths of water applied more frequently. They reported that improved drainage is necessary for reasonable crop production under shallow saline water table conditions.

Mathew *et al.*, (2001) evaluated the effect of drainage in improving soil quality and crop production. The results showed that many of the critical growth parameters, particularly the grain yield of rice (100 grain weight), were significantly higher in the well-drained areas than in the ill-drained areas because the salinity of the root zone could be controlled considerably by the subsurface drainage.

Asch and Wopereis (2001) studied the response of rice at different growing stages to floodwater salinity in order to derive guidelines for surface water drainage at critical growth stages in the Senegal River Delta. It was found that floodwater with an *EC* of 8 dS m^{-1} reduced germination by 50% and yield by 80%. Salinity strongly reduced spikelet numbers per panicle, and 100 grain weight. The strongest salinity effects on yield were observed around panicle initiation, whereas plants recovered best from salinity stress at seedling stage. Floodwater of < 2 $dS\ m^{-1}$ hardly affected rice yield. Floodwater of > 2 $dS\ m^{-1}$ around the panicle initiation stage reduced the yield by up to 1 t/ha per 2 $dS\ m^{-1}$. They concluded that drainage is necessary if floodwater EC > 2 $dS\ m^{-1}$ at critical growth stages.

In the Jezer'el Valley, Israel, a high water table caused by intensive irrigation and poor drainage led to the development of salinity problem. Benyamini *et al.,* (2005) found that, for successful control of salinity in the Valley, the water table must be at least 1.0 *m* below the soil surface. The combination of subsurface drainage and relief wells is the most efficient way to control water table.

Application of poor quality irrigation water and the upward flux of saline water from the shallow groundwater are causes of salinity build up in the root zone. The inability to leach these accumulated salts is the main reason for low crop transpiration and subsequent yield reduction. Irrigation, leaching, and drainage are the most important factors in controlling salinity in the root zone. A model of water and solute flow in conjunction with a crop yield response model is required to assess the impact of these variables on crop yield.

2.5 Conclusions

In this chapter evapotranspiration concepts, and the effect of water stress and salinity on crop growth and yield were reviewed. Many models have been developed to quantify the effect of non-standard conditions such as water and salinity stress. Some of these approaches calculate actual crop evapotranspiration and take into account only the effect of soil water stress and do not consider the reduction in crop transpiration caused by salinity stress. Other models consider the combined effect of both soil water and salinity stress on evapotranspiration. In these models complete recovery of the crop and the ability to continue transpiring at the potential rate is assumed after a stress event.

Crops have different sensitivities to water stress in different growth stages. Two types of crop water production function (additive and multiplicative) have been extensively used in research on crop water response to different amount of water supply. These functions are usually valid only under the conditions where they were developed. These functions need to be evaluated using experimental data to assess the relative sensitivity of each in application with the same water and salinity stress in order to select the most suitable function to be adopted for yield response modelling.

Irrigation, leaching and drainage are the key parameters affecting reliable and economic irrigation water management. Research on how crop yield responds to different irrigation, leaching and drainage practices at different growth stages is required in order to establish more productive irrigation water management strategies that maximise crop yield taking into account the effect of water and salinity stress.

CHAPTER 3

Evaluation of Crop Yield Response Functions

3.1 Introduction

Crop water production functions describe crop yield response to water availability. Many crop water production functions have been developed (Jensen, 1968; Minhas *et al.,* 1974; Stewart *et al.,* 1976; Doorenbos and Kassam, 1979; Martin *et al.,* 1984; and Rao *et al.,* 1988; de Wit, 1958). A number of functions were introduced in section 2.3.2. Many crop water production functions have the same basic form, in which crop yield is linearly related to cumulative actual evapotranspiration for the crop. Table 3.1 presents some well-known crop water production functions.

The existing functions are of two types: additive (Stewart *et al.,* 1976) and multiplicative (Jensen, 1968; Minhas *et al.,* 1974; Rao *et al.,* 1988). The Stewart and Rao functions are quite similar and divide the growing season into a number of stages with different yield response factors (K_y). These two functions use the yield response factors published in the FAO Irrigation and Drainage Paper No. 33 (Doorenbos and Kassam, 1979), which depend upon the crop type and its stage of growth. The main difference between these functions is that the Stewart function is additive whereas the Rao function is multiplicative. The Jensen and Minhas functions use a crop sensitivity factor (λ_i) for each stage of growth. λ is used as an indicator for the effect of water stress on crop yield. The higher the value of λ the greater the effect of water stress. The Doorenbos and Kassam, and Martin functions have exactly the same form in which K_y and b_e represent the slope of the linear relationship between relative evapotranspiration and relative yield. These functions cannot be used to evaluate the cumulative affect of water stress during the different growth stages. They can only be used to quantify the crop response to water at the end of a particular stage, or for the whole growing season.

Crop water production functions can be used for evaluating alternative irrigation scheduling strategies especially when water is a limited resource. The effect of water stress on crop yield and growth is dependent on the stage of growth during which the stress occurs. As a result, many irrigation scheduling strategies apply adequate amounts of water during the sensitive periods of crop growth to avoid high yield reduction. In these strategies, water applications can be reduced during the less sensitive stages with lower yield reduction.

Although yield response functions have been extensively used to quantify the yield-water relationship, there are still issues, particularly in relation to stages of growth. There is still a gap in knowledge in terms of the cumulative impact of water stress on crop yield in the different growth periods. Also, some of these functions are valid only for the conditions under which they were developed and parameters of the functions are location specific. As a result, some of these functions cannot be applied for irrigation water management in locations with different conditions from those where they were developed.

This chapter provides an evaluation of a number of crop water production functions to assess their relative sensitivity in application with the same water stress. The accuracy of the functions in calculating crop yield under different levels of evapotranspiration deficit is also examined.

Table 3.1: Some well-known crop water production function

Water production function	Author	Type	Limitations
$\frac{Y_a}{Y_m} = \prod_{i=1}^{n}\left(\frac{ET_a}{ET_m}\right)^{\lambda i}$	Jensen (1968)	Multiplicative	Difficulties in determining the sensitivity factor λ_i for each growth period
$\frac{Y_a}{Y_m} = \prod_{i=1}^{n}\left[1-\left(1-\frac{ET_a}{ET_m}\right)_i^2\right]^{b_i}$	Minhas et al (1974)	Multiplicative	Also due to difficulties in determining the sensitivity factor for each growth period
$\frac{Y_a}{Y_m} = 1-\sum_{i=1}^{n}K_i\left(1-\frac{ET_a}{ET_m}\right)_i$	Stewart et al (1976)	Additive	Can give very high yield reductions (Wardlaw and Barnes, 1996)
$\left(1-\frac{Y_a}{Y_m}\right) = K_y\left(1-\frac{ET_a}{ET_m}\right)$	Doorenbos and Kassam (1979)	-	It cannot be used to evaluate the cumulative affect of water stress during different stages of crop growth
$\frac{Y_a}{Y_m} = (1-b_e)+b_e\left(\frac{ET_s}{ET_m}\right)$	Martin et al (1984)	-	Difficulties in determining the factor b_e. Also it cannot be applied to evaluate the cumulative affect of water stress during the different stages of growth
$\frac{Y_a}{Y_m} = \prod_{i=1}^{n}\left[1-K_i\left(1-\frac{ET_a}{ET_m}\right)_i\right]$	Rao et al (1988)	Multiplicative	-

3.2 Assessment of crop yield response functions

An evaluation has been made of the crop water production listed in Table 3.1. In this evaluation, sorghum and cotton yields were calculated under different levels of water deficit. The Doorenbos and Kassam function (Doorenbos and Kassam, 1979) was used in the calculation of the sensitivity factor (λ) for the Jensen function for the individual growth stages, following the procedure described by Tsakiris (1982) as presented in Chapter 2.

The Stewart and Rao functions can be used with the crop yield response factors K_y published by Doorenbos and Kassam (1979). Since the Doorenbos and Kassam and Martin functions are exactly the same, the Martin function is considered no further. For the Jensen and Minhas functions the coefficients were derived from the Doorenbos and Kassam (1979) data also.

The Doorenbos and Kassam function has been used by irrigators, economists and policy makers to assess their plans and scenarios for investment in the agricultural sector. However, the FAO expert meeting on crop water productivity, held in February 2003 in Rome, considered it important that the function be revised to be able to quantify the crop yield response under very limited water supply. The parameters and procedures described in the FAO Irrigation and Drainage Paper No. 33 (Doorenbos and Kassam, 1979) require updating and refinements in order to reflect the increase in productivity of the major crops over the last 25 years (FAO, 2003).

The problem with using the Doorenbos and Kassam function is that it cannot be used to quantify the effect of water stress on crop yield cumulatively. No guidance is given by Doorenbos and Kassam on how to apply the yield response function when water shortage occurs cumulatively during different stages of crop growth. As mentioned earlier in Chapter 2, this function can only be used to predict reduction in crop yield at the end of each stage of growth separately as well as at the end of the growing season based on the crop reduction factors published in Doorenbos and

Kassam, (1979). However, Smith (1992) in the CROPWAT program has used Doorenbos and Kassam function in a cumulative way where each yield reduction for a given stage is carried over to the next stage according to:

$$\left(1 - Y_a / Y_m\right)_i = 1 - \left(Y_a / Y_m\right)_1 * \left(Y_a / Y_m\right)_2 * ......\left(Y_a / Y_m\right)_i \qquad (3-1)$$

where, 1,2…i is stage of growth.

Smith (1992) has basically used the same procedure as the Rao function. Adopting this procedure for the Doorenbos and Kassam function, an evaluation has been made of the functions listed in Table 3.1. With the exception of the Stewart function, all other functions produce exactly the same results. The Stewart function, which is the only additive function in this comparison, gives generally lower relative yields than other functions in the range of evapotranspiration deficits considered. Figures 3.1 and 3.2 show that the different functions behave in the same way on sorghum and cotton. The results presented are for the entire growing season, but are calculated on the basis of the same evapotranspiration deficit occurring in each growth stage. Figures 3.3 and 3.4 show the impact of using the Doorenbos and Kassam seasonal coefficients, rather than stage of growth coefficients. Higher relative yield is predicted than when the stage of growth coefficients are used. This is a shortcoming of the function, and the effect of water stress should be taken into account cumulatively over the different growth stages.

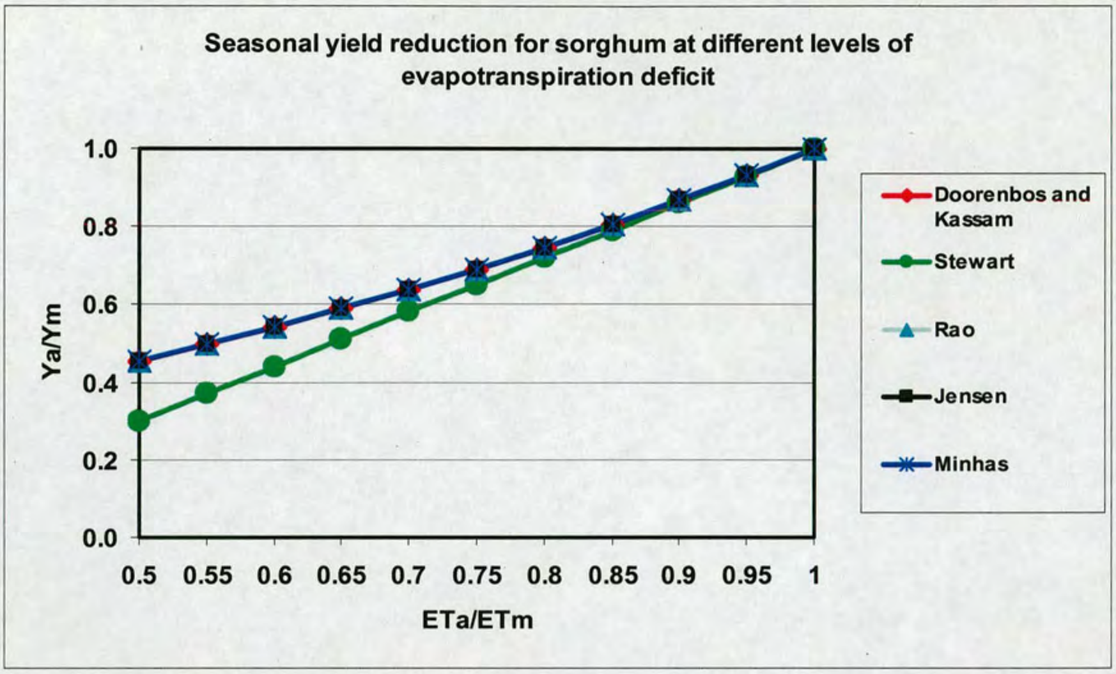


Figure 3.1: Comparison of yield response functions for sorghum

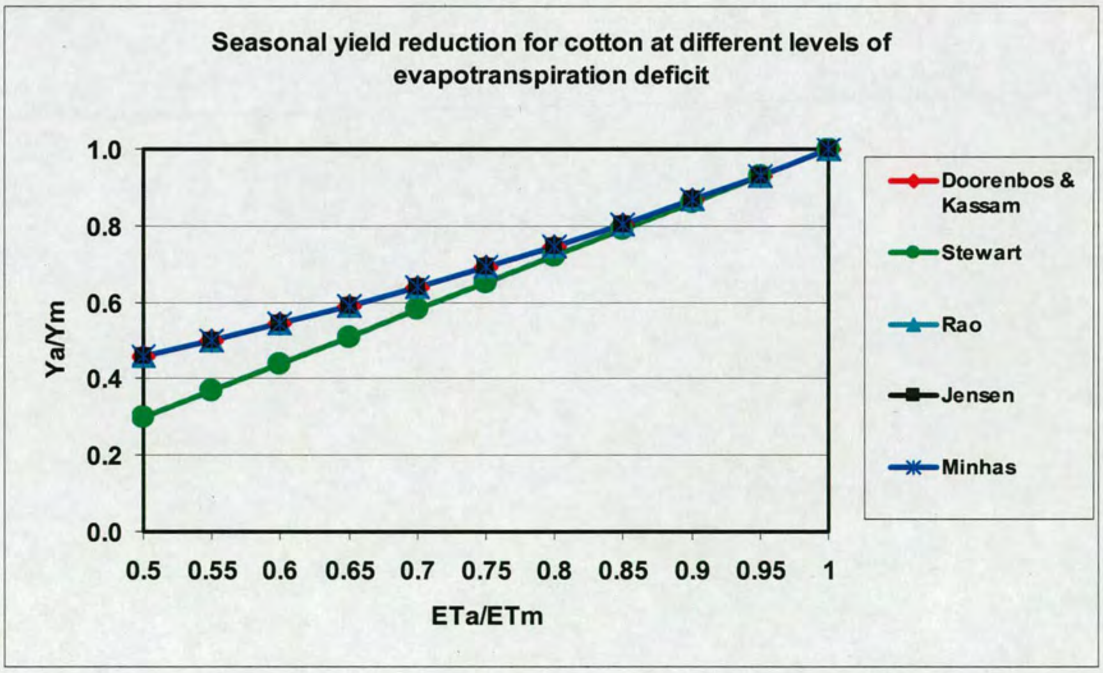


Figure 3.2: Comparison of yield response functions for cotton

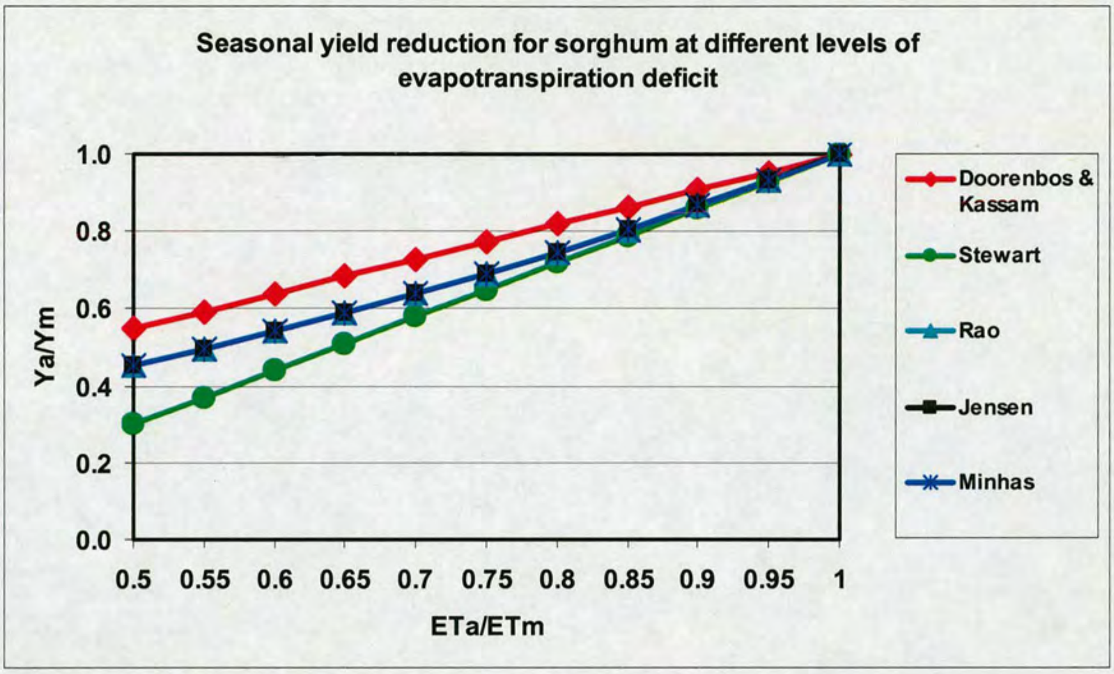


Figure 3.3: Comparison of yield response functions for sorghum using Doorenbos and Kassam seasonal coefficient.

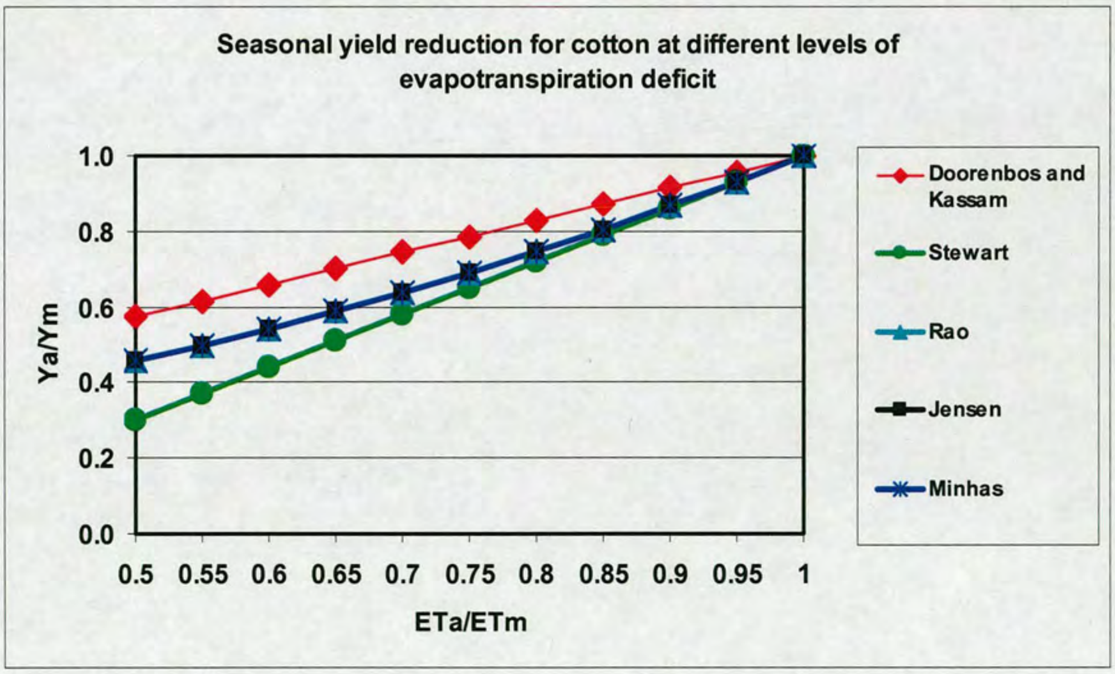


Figure 3.4: Comparison of yield response functions for cotton using Doorenbos and Kassam seasonal coefficient.

Figures 3.5 and 3.7 show the relative yields for sorghum and cotton at each stage of crop growth with each of the functions, as well as the seasonal relative yield under 50% evapotranpiration deficit. 50% evapotranspiration deficit is the lower limit at which K_y was determined by the Doorenbos and Kassam. Since the coefficients for each function were derived from the linear relationships between relative yield and relative evapotranspiration published by Doorenbos and Kassam (1979), the stage by stage results are the same using all functions except Stewart function which gives a lower stage by stage relative yield as well as a lower seasonal relative yield than the Rao, Jensen and Minhas functions in flowering, yield formation and ripening growing stages. The Doorenbos and Kassam function gave exactly the same stage by stage relative yield as other functions as the effect of water stress on crop yield was applied cumulatively. However, when applied with seasonal coefficients, the Doorenbos and Kassam function gives a higher seasonal relative yield than the other functions. However, under 10% evapotranspiration deficit, all functions, gave approximately similar values of relative yield for the individual growth stages (Figures 3.6 and 3.8).

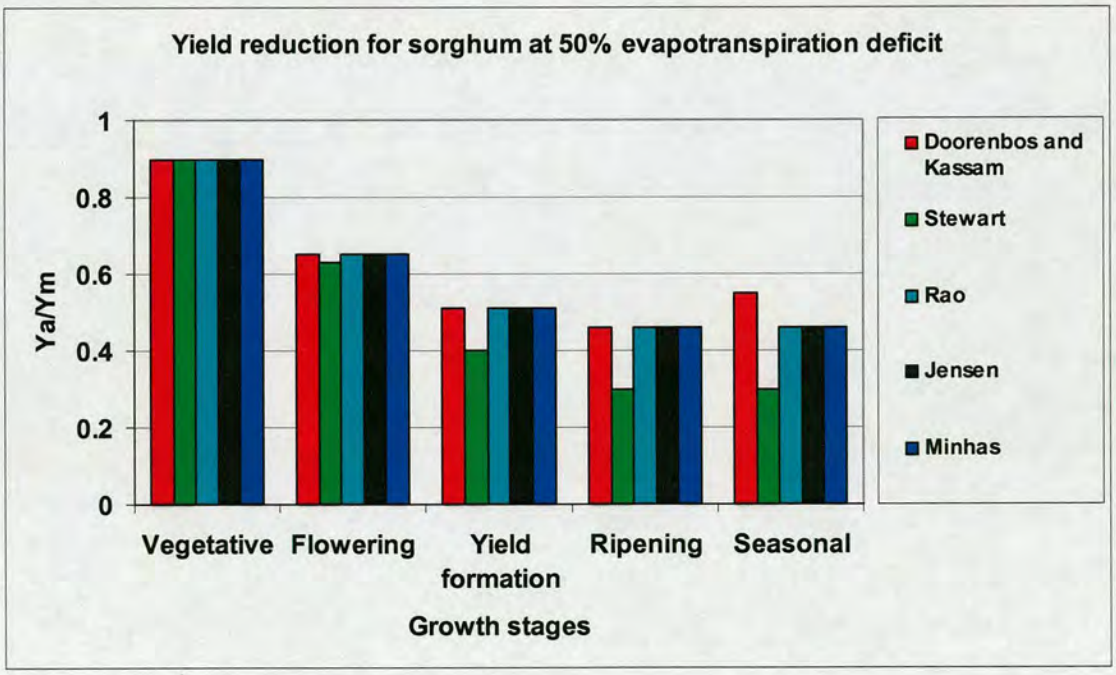


Figure 3.5: Sorghum yield reduction in different stages of crop growth

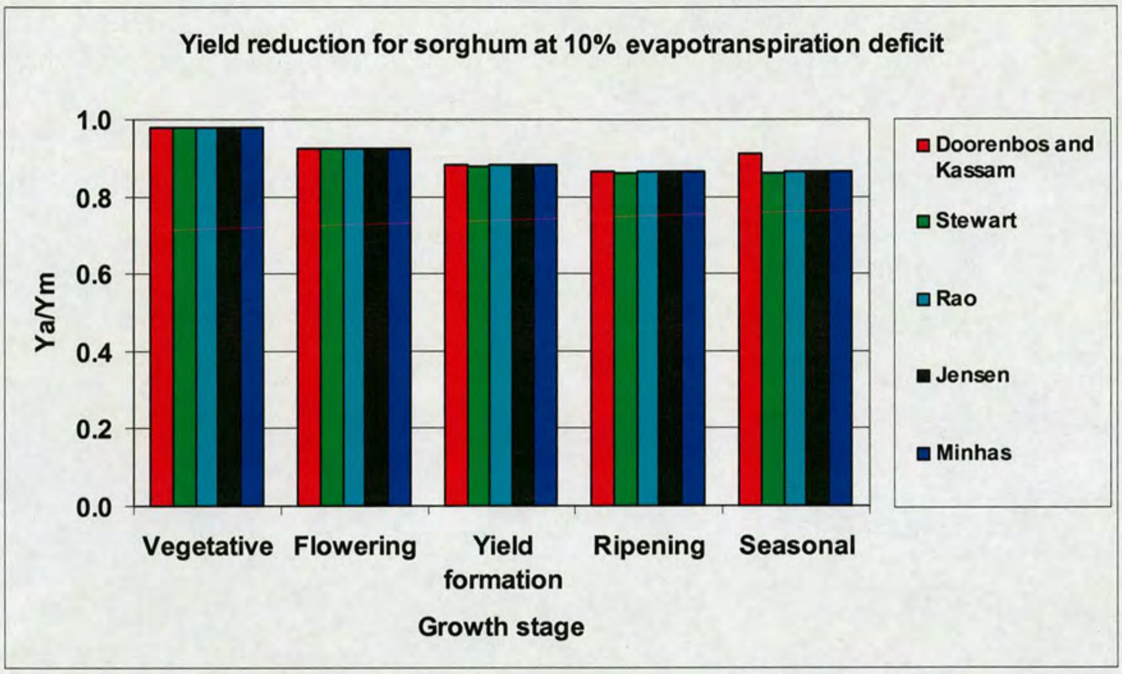


Figure 3.6: Sorghum yield reduction in different stages of crop growth

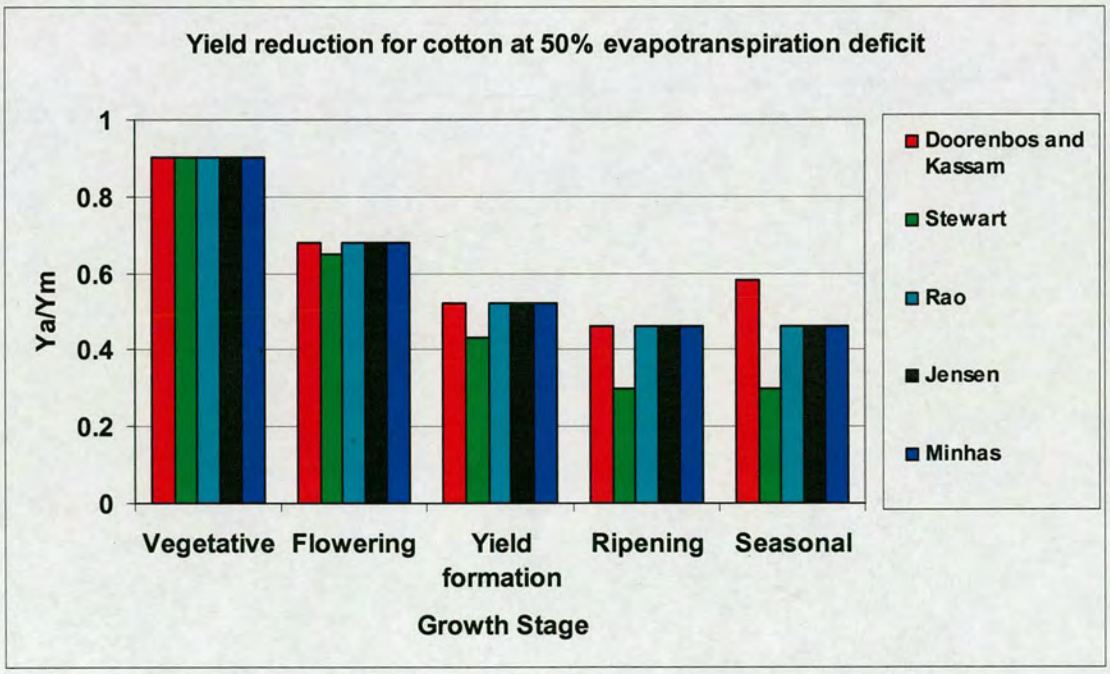


Figure 3.7: Cotton yield reduction at different stages of crop growth

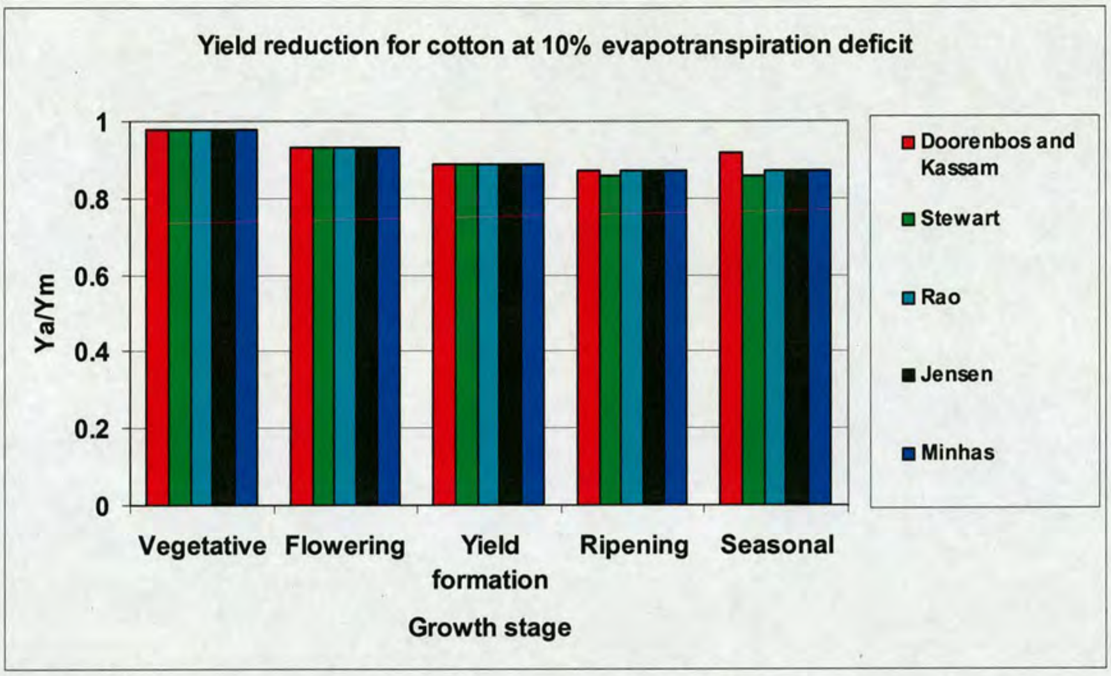


Figure 3.8: Cotton yield reduction at different stages of crop growth

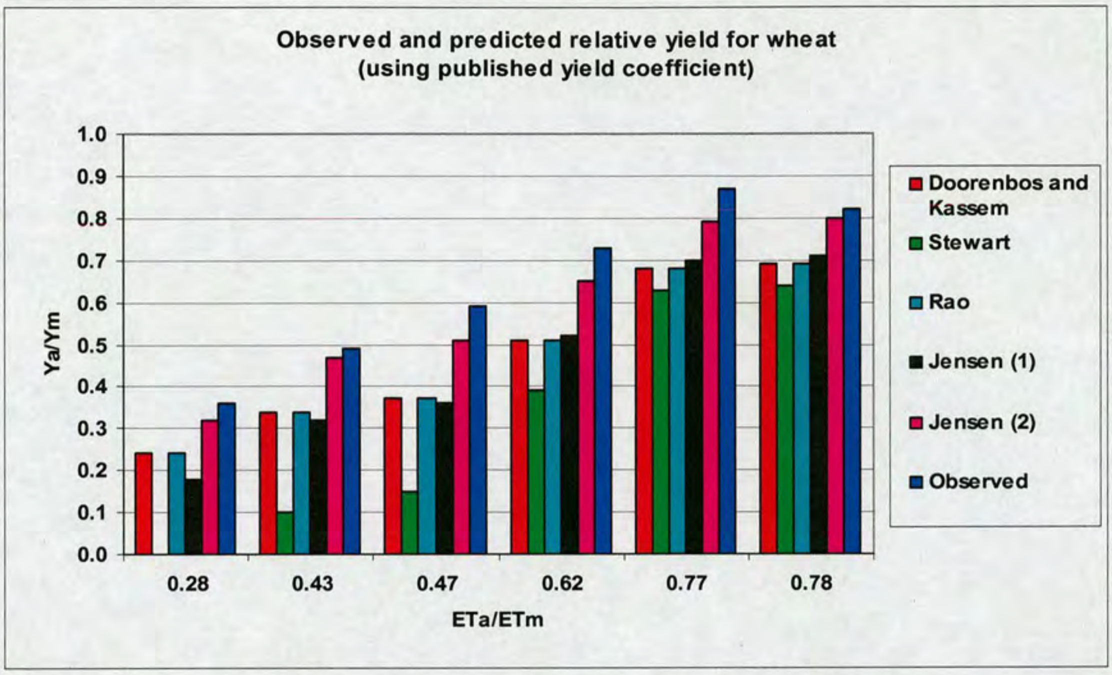
For both sorghum and cotton, the flowering and yield formation stages are the most sensitive to water stress. Since vegetative and ripening growth stages are considered as the least sensitive to water stress for both crops, the amount of water to be applied can be reduced in these stages with minimum yield reduction.

A further evaluation was carried out in which seasonal relative wheat yields obtained using the functions (with published yield coefficients) were compared with experimental seasonal yield data from New Zealand (Jamieson *et al.,* 1998). The published yield coefficients for Doorenbos and Kassam, Stewart and Rao functions were taken directly from FAO Irrigation and Drainage Paper No. 33. However, crop yield sensitivity factor for the Jensen function at different growing stages were taken from Zhang and Oweis (1999) for the area of Tel Hadya in Syria. Another crop sensitivity factor for the Jensen function was used in which λ for the individual growth stages was derived from Doorenbos and Kassam function according the procedure described by Tsakiris (1982).

Figure 3.9 shows variations between measured relative yield and relative yield obtained using the various functions. A decrease in yield with increasing evapotranspiration deficit was calculated with all functions. All functions gave approximately similar values of relative seasonal yield, which was lower than that observed under all levels of evapotranspiration deficit considered. However, the variations between measured relative yield and relative yield obtained using the functions were not significant. The Stewart function gave lower crop yields than those obtained using other functions, especially at high evapotranspiration deficit. In addition, the Jensen function when used with crop sensitivity factors taken from Zhang and Oweis (1999) gave a higher value of relative seasonal yield than other functions, that was closer to the observed under all evapotranspiration levels considered.

Table 3.2: Published seasonal yield coefficients for wheat.

Coefficient	Stage 1	Stage 2	Stage 3	Stage 4	Source
K_y	0.2	0.6	0.5	-	Doorenbos and Kassam (1979)
λ	0.16	0.57	0.47	0.16	Derived from Doorenbos and Kassam (1979)
λ	0.15	0.31	0.17	0.26	Zhang and Oweis (1999)



Jensen (1): Crop sensitivity factors were derived using Doorenbos and Kassam function
Jensen (2): Crop sensitivity factors were taken from Zhang and Oweis (1999)

Figure 3.9 Observed and predicted wheat yields under different water stress levels

The above results indicate that the yield response functions produce reasonable results with published yield response factors. The results are conservative. However, local experimental data are required in order to establish more reliable crop yield coefficients.

3.3 Conclusions

This chapter provides an evaluation of a number of crop yield response functions. The relative sensitivity of each function in application with the same water stress has been assessed. As the coefficients for each function were derived from the linear relationships between relative yield and relative evapotranspiration published by Doorenbos and Kassam (1979), the stage-by-stage results are approximately the same using all functions. When using published crop yield coefficients, all functions gave approximately the same results.

In a comparison with experimental data, all functions gave reasonable predictions of yield under a range of water stress levels when using published seasonal yield coefficients. It is apparent that all functions would be suitable for yield response modelling. Yield response coefficients are influenced by local conditions, and a wider data set of coefficients than is currently available is desirable.

CHAPTER 4

Variably Saturated Flow Models

4.1 Introduction

Understanding water flow and solute transport in the vadose zone is essential to establish efficient irrigation and drainage practices for sustainable crop production. Computer models based on numerical solution of the equations describing water and solute transport in the vadose zone can be used to assist in assessing the impact of water and salinity stress on crops, and to establish sustainable irrigation and drainage practices.

Many models that simulate water and solute flux in the soil-crop system have been developed (Vanclooster *et al.,* 1994; Simunek *et al.,* 1996; Simunek *et al.,* 1999; Van Dam *et al.*, 1997; Zhang and Dawes, 1998; Wang *et al.,* 2001; Ragab, 2002). These models deal with physical and chemical processes describing water and solute transport within the soil, plant and climate system and the interactions between these system components. Most models are one-dimensional, and different models have their own advantages and disadvantages. Effective use of these models requires accurate input parameters such as soil water retention and unsaturated hydraulic conductivity data (Simunek *et al.,* 1998). The Richard's equation for water flow and the advection-dispersion equation for solute transport are generally at the core of the models. An extensive review of the vadose zone models was carried out recently by MDH Engineering Solutions Corp. (2003). They evaluated 43 codes for their ability to predict water flow and solute transport in the soil and groundwater systems. All of the chosen codes were available in the public domain. Of the 43 models evaluated, only 5 (VS2DI, SEVIEW, HYDRUS, UNSATCHEM and CHEMOFLO) were considered to be highly ranked codes. These have excellent documentation, good user interfaces, and provide numerous examples for validation and tutorial purposes.

This chapter provides a review of the most important theoretical concepts of some existing variably unsaturated flow models.

4.2 Models Overview

As a part of this research, a review was carried out of six codes for water and solute transport in the vadose zone. These codes, all of which have been quite widely used, are:

- WAVE (Vanclooster *et al.,* 1994);
- UNSATCHEM (Simunek *et al.,* 1996);
- WAVES (Zhang and Dawes, 1998; Wang *et al.,* 2001; Kang *et al.,* 2003);
- SWAP (Van Dam *et al.,* 1997; Van Dam, 2000);
- HYDRUS-2D (Simunek *et al.,* 1999);
- SALTMED (Ragab, 2002).

The WAVE model (**W**ater and **A**grochemicals in soil and **V**adose **E**nvironment, Vanclooster *et al.,* 1994) is a one-dimensional mathematical model developed by researchers of the Institute for Land and Water Management at the Katholieke University of Leuven in Belgium. WAVE is a deterministic numerical model that simulates the transport and transformations of water, heat and solute in the soil, crop and vadose environment. The model consists of five modules; a water transport module, a solute transport module, a heat transport module, a crop growth module, and a nitrogen fate module. The model is an integration of earlier models such as SWATRER (water module) (Feddes *et al.,* 1978; Belmans *et al.,* 1983; Dierckx *et al.,* 1986), SOILN (nitrogen module) (Bergstrom *et al.,* 1991), LEACHN (heat and solute module) (Wagenet and Hutson, 1989) and SUCROS (crop growth model) (van Keulen *et al.,* 1982; Spitters *et al.,* 1988). A finite-difference technique is used to solve the differential equations describing the water and solute transport processes. The WAVE model is written in FORTRAN 77 and can be run on either UNIX or MS-DOS platforms.

The UNSATCHEM model was developed by the U.S. Salinity Laboratory of the U.S. Department of Agriculture. It simulates water flow, multi-component solute transport, heat transport and carbon dioxide transport, in the vadose zone. It is one of the few models simulating multi-component solute transport with major ion equilibrium and kinetic chemistry in variably saturated flow. The model can be used to evaluate the performance of various management practices as it considers water flow, chemical processes and transport, plant water uptake which is related to osmotic and matric stress, as well as the effect of chemistry on soil hydraulic properties (Simunek *et al.,* 1996).

The WAVES model (Zhang and Dawes, 1998; Wang *et al.,* 2001; Kang *et al.,* 2003) is a one-dimensional model that simulates the following processes on a daily time step:

- interception of rainfall and light by canopy;
- surface energy balance;
- carbon balance and plant growth;
- soil evaporation and plant transpiration;
- surface runoff and infiltration;
- soil water content with depth;
- drainage;
- solute transport;
- water table interactions.

The model consists of four modules: energy, water, carbon (plant growth), and solute balances modules.

The SWAP (**S**oil-**W**ater-**A**tmosphere-**P**lant) model is a one-dimensional physically based model for vertical water, heat and solute transport in the saturated and unsaturated zones. SWAP has a long development history dating from work by the Water Resources Group of Wageningen University in the late 1970s (Feddes et al., 1978). The current version of the model is attributable to Van Dam, (2000). SWAP version 3.0.3 is now available with a very thorough technical manual (Kroes and Van Dam, 2003). It is designed for integrated modelling of the soil-water-atmosphere-plant system. It also includes modules for simulating irrigation, drainage practices and crop growth and yield. SWAP is also written in FORTRAN 77. The current version of the model in available free of charge and source code access is also available. SWAP was not widely available at the start of this research project, however.

The HYDRUS-2D models (Simunek *et al.,* 1999) are deterministic, physically based, numerical models, that simulate one and two-dimensional unsaturated flow, heat movement and multiple solutes transport in soil. They were developed by the U.S. Salinity Laboratory of the U. S. Department of Agriculture. The models solve the Richard's equation for saturated-unsaturated water flow, convection-dispersion equations for heat and solute transport. HYDRUS-2D is very similar to the UNSATCHEM model but does not model crop yield. The input data for HYDRUS-2D are similar to those required for UNSATCHEM model except that a carbon dioxide transport and crop production information file is not required for HYDRUS-2D.

The SALTMED model (Ragab, 2002) is a physically based model that offers sound numerical solutions for water and solute flow in one or two dimensions. It calculates evapotranspiration, soil evaporation, plant water uptake, leaching requirements, soil salinity profiles, soil moisture profiles and crop yield. The model can be applied with any irrigation system, as well as to rain fed agriculture. In the model, Richard's equation and the convection-dispersion equations describe the water and solute transport, respectively. The code of the model was written in C/C^{++} for Windows 95, 98, 2000 and Windows XP operation systems. The model output is given as a text and graphical files.

4.3 Process Description

4.3.1 Variably saturated flow

The six codes described above simulate transient flow by numerically solving the one-dimensional Richard's equation for a set of boundary conditions using a finite differences technique. The Richard's equation combines Darcy's law and the continuity equation. The Richards' equation is written as (Vanclooster *et al.,* 1994):

$$\frac{\delta\theta}{\delta t} = \frac{\delta}{\delta z}\left[K(\theta)\left(\frac{\delta h}{\delta z} + 1 \right) - S(z,h) \right] \tag{4-1}$$

where, θ is the volumetric moisture content $(m^3\ m^{-3})$;

z is the vertical co-ordinate (m);

$K(\theta)$ is the hydraulic conductivity $(cm\ day^{-1})$;

h is the soil water pressure head (cm);

$S(z,h)$ is the water uptake by plant roots (day^{-1})

In the WAVE model, the upper boundary condition is defined by a flux through the soil surface. The lower boundary condition can be defined in a number of ways: a groundwater level boundary condition, a pressure head boundary condition, a flux through the bottom of the model or free outflow at the bottom of the model (Vanclooster *et al.,* 1994). The boundary conditions in the WAVE model are discussed in more detail in Chapter 5.

The water flow model in the HYDRUS-2D and UNSATCHEM models can deal with constant or time-varied hydraulic head or flux boundaries controlled by atmospheric conditions. They can also deal with seepage face and free drainage boundary conditions (Simunek *et al.,* 1996; Simunek *et al.,* 1999).

In the SWAP model, the upper boundary conditions of the system are determined by potential evapotranspiration, irrigation and precipitation. The bottom boundary condition is located in the unsaturated zone or in the upper part of the groundwater, and describes the interaction with groundwater. It is possible to have flux specified, pressure head specified and flux-groundwater level relationships (Van Dam, 2000).

In the SALTMED model, the upper boundary conditions of the system are determined by potential evapotranspiration, irrigation and precipitation. However, the model deals only with a free drainage or an impermeable lower boundary condition (Ragab *et al.,* 2003). It is not clear from the literature if the model is able to deal with a water table, and the contribution that the water table can make to water and solute flow in the unsaturated zone through capillary action.

In the unsaturated zone, soil moisture and soil moisture tension, or pressure head, are linked, and in order to apply the Richard's equation this relationship, known as the water retention curve, must be defined. A number of functions are available, such as van Genuchten (1980), Brooks and Corey (1964), modified van Genuchten type model or the Broadbridge and White (1988) function. These functions require several input parameters. The van Genuchten (1980) function can be written as follows (Vanclooster *et al.*, 1994; Simunek *et al.*, 1996; Van Dam, 2000, Ragab, 2002):

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + (\alpha|h|)^n\right)^m} \qquad h < 0 \qquad (4-2)$$

$$\theta(h) = \theta_s \qquad h \geq 0 \qquad (4-3)$$

where, θ_s is the saturated volumetric soil water content $(m^3\ m^{-3})$

θ_r is the residual volumetric soil water content $(m^3\ m^{-3})$

α is the inverse of the air entry (m^{-1})

n, m are shape parameters

It requires the saturated water content, residual water content, the inverse of the air entry α, and the shape parameters n and m. The WAVE, UNSATCHEM, SWAP and SALTMED models use the van Genuchten (1980) function.

The Brooks and Corey (1964) model for water retention may be written as (Simunek *et al.*, 1999):

$$S_e = |\alpha h|^n \qquad h < -1/\alpha \qquad (4-4)$$

$$S_e = 1 \qquad h \geq -1/\alpha \qquad (4-5)$$

where, S_e is the effective water content,

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad (4-6)$$

HYDRUS-2D can describe unsaturated soil hydraulic properties using the van Genuchten (1980), or Brook and Corey (1964) functions.

The model of Broadbridge and White (1988) is used in the WAVES model to describe the relationship between water potential, volumetric water content and hydraulic conductivity. This model requires five parameters: saturated hydraulic conductivity, volumetric moisture content at saturation, air-dry volumetric water content, the soil capillary length scale and a soil structure parameter (Wang *et al.*, 2001).

Most variably unsaturated flow models have a number of optional functions to describe unsaturated hydraulic conductivity characteristics. These can be expressed in terms of pressure head or volumetric moisture content (Gardner, 1958; Gilham *et al.,* 1976; Brooks and Corey, 1964; van Genuchten, 1980; Mualem, 1976). Only three functions are presented as examples in this review. These are Gardner, (1958), Mualem (1976) and Brooks and Corey (1964).

The functions are described by Vanclooster *et al.,* (1994), and are:

Gardiner (1958): $$K(h) = K_s e^{\alpha h} \qquad (4-7)$$

Mualem (1976): $$K(h) = K_s S_e^{\lambda}\left[1-\left(1-S_e^{1/m}\right)^m\right]^2 \qquad (4-8)$$

Brooks and Corey (1964): $$K(S_e) = K_s S_e^{\left(\frac{2+3*\lambda}{\lambda}\right)} \qquad (4-9)$$

where, K_s is the saturated hydraulic conductivity $(L\,.\,day^{-1})$

λ is the tortuosity factor which can be fixed to 0.5.

In the SWAP, UNSATCHEM, HYDRUS-2D and SALTMED models the Mualem function (Mualem, 1976) is used. In addition, the UNSATCHEM model considers the effects of chemical composition on hydraulic conductivity (Simunek *et al.,* 1996). The unsaturated hydraulic conductivity model of Broadbridge and White (1988) is used in the WAVES model (Zhang and Dawes, 1998), while in the WAVE model, all of the above functions are available.

4.3.2 Evapotranspiration

The Richard's equation includes a sink term to model water uptake by plant roots. Water uptake is derived from potential crop evapotranspiration. In the WAVE, UNSATCHEM and HYDRUS-2D models, potential crop evapotranspiration (ET_p) is required as an input. However, in the WAVES, SWAP and SALTMED models, ET_p is calculated using Penman-Monteith equation (Monteith, 1981; Smith *et al.*, 1992; Allen *et al.*, 1998). In all models under review, ET_p is partitioned into potential soil evaporation (E_p) and potential crop transpiration (T_p) on the basis of leaf area index (LAI). The SWAP model uses the following functions to split ET_p into E_p and T_p:

$$E_p = ET_p.e^{-K_{gr}LAI} \qquad (4-10)$$

$$T_p = \left(1 - \frac{P_i}{ET_p}\right)ET_p - E_p \qquad (4-11)$$

where, P_i is the interception amount (L)

T_p is transferred to potential water uptake by plant roots from different soil layers depending on root length and distribution. Water shortage and salinity reduce root water uptake and their effect is considered by multiplying the potential root water uptake in each soil layer by water and salinity stress reduction factors. The UNSATCHEM, HYDRUS-2D models take into account the combined effect of water and salinity stress on root water uptake according to the function proposed by Feddes *et al.*, (1978) and modified by van Genuchten, (1987) to include the effect of salinity on osmotic stress.

The SALTMED model considers the effect of both soil water and salinity stress according to the model suggested by Cardon and Letey, (1992) as:

$$S_{(z,t)} = \left[\frac{S_{\max}(t)}{1 + \left(\frac{a(t)h + \pi}{\pi_{50}(t)} \right)} \right] \lambda(z,t) \qquad (4-12)$$

$$\lambda_{(Z)} = 5/3L \quad \text{for } z \le 0.21 \qquad (4-13a)$$

$$\lambda_{(Z)} = 25/12L * (1 - z/L) \quad \text{for } 0.2L < z \le L \qquad (4-13b)$$

$$\lambda_{(Z)} = 0.0 \quad \text{for } z > L \qquad (4-13c)$$

where, $S(z,t)$ is water and salinity stress-adjusted value of potential root water uptake $\left(day^{-1}\right)$,

$S_{\max}(t)$ is the maximum potential root water uptake at the time t $\left(day^{-1}\right)$,

z is the vertical depth (positive downward) (cm),

$\lambda(z,t)$ is the depth and time-dependent fraction of total root mass,

L is the maximum rooting depth (cm)

h is the matric pressure head (cm)

π is the osmotic pressure head (cm)

π_{50} is the value of osmotic pressure head at which root water uptake is reduced by 50% (cm),

a is a coefficient equal to π_{50}/h_{50}, where h_{50} is the value of soil water pressure head at which crop transpiration is reduced by 50%.

The WAVE model considers only the effect of water stress on crop transpiration according to the model proposed by Feddes *et al.,* (1978). The SWAP model takes into account the combined effect of water and salinity stress according to the function presented by Homaee (1999), which is a combination of the reduction function of Feddes *et al.,* (1978) with that of Maas and Hoffman (1977). This requires input of salinity threshold EC values, above which, salinity stress occurs. All of the above-mentioned functions are discussed in Chapter 2.

In the WAVES model, soil evaporation and plant transpiration are calculated separately using the Penman-Monteith equation (Monteith, 1981). The effect of salinity on plant growth is modelled in terms of its effect on the availability of soil water to plant roots due to the osmotic potential induced by dissolved salts. The availability of water to the plant is calculated as (Zhang and Dawes, 1998):

$$X_w = \sum_{i=1}^{N} \frac{\left(1 - \frac{\Psi_i + \eta \Pi_i}{\Psi_{wilt}}\right) \Delta z_i}{z_{\max}} \qquad (4-14)$$

where, X_w is the relative availability of water,

Ψ_i is the water matric potential (m) at node i,

Ψ_{wilt} is the matric potential at wilting point (m),

Π_i is the osmotic potential (m) at node i,

N is number of nodes,

$z_{\max}$ is the maximum rooting depth.

Transpiration is distributed within the rootzone according to the following equation (Zhang and Dawes, 1998):

$$rw_i = E \frac{rp_i \left(1 - \frac{\psi_i + \eta \Pi_i}{\Psi_{wilt}}\right)}{SRP} \qquad (4-15)$$

where, rw_i is the root water demand at depth node i $(m.d^{-1})$,

rp_i is the proportion of total root mass at node i,

SRP is the sum of numerator overall all nodes.

4.3.3 Solute Transport

All six models under consideration in this review solve convection-dispersion type equations for solute transport. However, solute transport in the HYDRUS-2D model considers diffusion in the gaseous phase in addition to the convective and depressive transport in the liquid phase. The widely applied convection-dispersion equation is written as (Vanclooster *et al.,* 2000b):

$$\frac{\delta(\theta C)}{\delta t}+\frac{\delta(\rho K_d C)}{\delta t}=\frac{\delta}{\delta z}\left[\theta D\frac{\delta C}{\delta z}\right]-\frac{\delta(q_w C)}{\delta z}+Sinksol \qquad (4-16)$$

where, C is the soil solute concentration $(kg\ m^{-3})$;

θ is the volumetric water content $(m^3\ m^{-3})$;

K_d is the distribution coefficient $(m^3\ kg^{-1})$;

D is the dispersion coefficient $(m^2\ day^{-1})$;

q_w is the Darcian water flux $(m^3\ m^{-2}\ day^{-1})$;

ρ is the apparent density $(kg\ m^{-3})$;

t is the time (day);

$Sinksol$ is the solute sink term $(kg\ day^{-1})$

The distribution coefficient K_d is defined as the ratio of the adsorbed solute content to the solute concentration in solution at equilibrium. In other words, it indicates the tendency of solutes to adsorb to the soil particles. K_d can be considered as a very variable and unpredictable parameter. Its value depends on solute and soil characteristics and may range between several magnitudes (Baes and Sharp, 1983). K_d is very important parameter in modelling solute transport in soil as it controls the adsorption of solutes on soil complex. In other words, it has a great influence on the rate at which salinity builds up, or is leached. A high value of K_d, lead to greater adsorption of solutes and simulated leaching of solutes would be less effective than with a lower value of K_d. Persicani, (1996) reported that, with decreasing K_d value from 1.0 ml/g to 0.4, the cumulative atrazine loss below the topsoil increased from 41% to 70%. Accordingly, this parameter can be the key parameter in calibrating soil salinity and obtaining reasonable salinity levels that reflects the real situation.

For modelling solute transport, the WAVE model considers a physical non-equilibrium concept, assuming convection-dispersion flow in the mobile soil region together with rate-limited exchange between the mobile and immobile soil regions. A flux type (solute flux mass) boundary condition is used to define the top boundary condition. The lower boundary condition is a zero concentration gradient at the bottom of the flow domain.

The UNSATCHEM model considers Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, $SO_4^{\ 2-}$, Cl^{-}, $NO_3^{\ -}$, H_4SO_4, alkalinity, and CO_2 as major variables of the chemical system. The model accounts for the equilibrium chemical reactions between these components such as complexation, cation exchange and precipitation-dissolution. Of the five models under consideration, only the UNSATCHEM model considers the precipitation-dissolution of calcite and dissolution of dolomite either by equilibrium or multi-component kinetics including both forward and backward reactions. The cation exchange between the solid phase and solution is described using the Gapon equation (White and Zelazny, 1986). Other dissolution-precipitation reactions considered include gypsum, hydromagnesite, nesquehonite, and sepiolite.

In the HYDRUS-2D model, the solute transport equations consider the following:

- advection-dispersion transport in the liquid phase;
- diffusion in the gas phase;
- non-linear non-equilibrium reactions between solid and liquid phases;
- linear equilibrium reactions between the liquid and gaseous phases;
- two first order degradation reactions; degradation reactions independent of other solutes, and degradation reactions which couple the solutes involved in sequential first order decay reactions.

The solute transport model in the HYDRUS-2D and UNSATCHEM models supports constant or time-variable concentration and concentration flux boundary conditions.

4.3.4 Crop Yield Response

Of the five models reviewed, WAVE and HYDRUS-2D are unable to assess the combined effect of irrigation water applications, leaching amounts, and drainage rates on crop yield since they do not include any crop yield response function. In the WAVE model, the crop growth model can calculate the time course of the leaf area index, the accumulation of the dry matter of the different plant organs and the root length and root density extension rate, but this does require a significant amount of data.

Crop yield in the SWAP and UNSATCHEM models is modelled using the crop production functions proposed by Doorenbos and Kassam (1979) and Stewart *et al.*, (1976), respectively. These functions were discussed in Chapters 2 and 3. Crop yield response to water is computed in the WAVES model according to the model proposed by de Wit (1958) as:

$$Y = Y_m . m \frac{ET_a}{ET_p} \qquad (4-17)$$

where, Y_m is the maximum grain yield,

m is an empirical constant,

ET_p is the potential crop evapotranspiration over the growing season (m),

ET_a is the actual crop evapotranspiration over the growing season (m).

The SALTMED model uses the following function to compute crop yield (Ragab, 2002):

$$Yr = \frac{\sum S(t)}{\sum S_{\max}(t)} \qquad (4-18)$$

where, Yr is the relative yield,

$S_{\max}(t)$ is the potential root water uptake at the time t $\left(day^{-1}\right)$,

$S(t)$ is the actual root water uptake over the season (day^{-1}).

The above function is basically the same as the de Wit (function) except that there is no constant.

The actual yield is simply obtained by (Ragab, 2002):

$$Y_a = Yr * Y_m \qquad (4-19)$$

where, Y_a is the actual yield,

Y_m is the maximum yield obtained under optimum conditions.

4.4 Strengths and Weaknesses

4.4.1 WAVE

One of the advantages of the WAVE model is that it is programmed in a modular way, which makes it relatively easy to incorporate new concepts and routines without the need to significantly change the model structure or its input files (Vanclooster *et al.,* 1994). Other advantages of the WAVE model are:

i) it is able to assess the contribution from the water table by capillary flux in partially meeting crop water requirements;

ii) it provides physics based modelling of soil moisture movement, solute transport and root development;

iii) it is also able to assess the influence of the water table on the salinity levels in the root zone;

iv) model source code is available.

Three weaknesses have been identified:

a) the model calculates actual crop transpiration assuming that the crop is only under the effect of soil water stress, it is not be able to take into account the combined effect of water and salinity stress on crop transpiration, which makes it less applicable under salinity conditions;

b) it is unable to assess the combined effect of irrigation water applications, leaching amounts, and drainage rates on crop yield since it does not include any crop yield response function; its' crop growth module calculates the time course of the leaf area index, the accumulation of the dry matter of the different plant organs and the root length and root density extension rate and requires a lot of parameters.

c) the maximum simulation period is limited to one year; this is a limitation particularly in application to salinity management problems as it can take several years for the impacts of any particular water management practice to be observable, or to significantly affect crop yield (Mott MacDonald, 2000b).

4.4.2 UNSATCHEM

The UNSATCHEM model is recommended for reactive transport modelling when sodium adsorption ratio $(SAR)$and electrical conductivity (EC) are required (MDH Engineering Solutions Corps., 2003). The strengths of this model are as follows:

i) it is able to model complex soil-water-plant interactions especially the reactive transport of multiple species and their effect on crop transpiration and subsequently on crop yield;

ii) it is able to simulate cation exchange reactions;

iii) it considers the effect of chemical composition on hydraulic conductivity;

iv) input parameters are relatively straightforward to define.

v) it includes a crop yield response function.

Its weaknesses are that:

a) it cannot be used for long-term simulation; it can only run for maximum one year;

b) it doesn't take into account solutes added to the soil profile through irrigation water;

c) it is limited to modelling a specific set of major ions;

d) although it can model precipitation/dissolution reactions, it is limited in its ability to model sorption/desorption and decay processes;

e) the specification of boundary conditions is complex;

f) in the calculation of crop yield, the model assumes that the effect of water stress is the same during all growth stages; it doesn't consider the different sensitivity of growth stages to water deficit.

4.4.3 WAVES

WAVES is applicable in a wide range of conditions. It was not developed for any particular climatic region, soil type or vegetation system. It also includes a wide range of dynamic processes. The WAVES model allows long-term simulations depending on how much climatic data are available or can be generated (Zhang and Dawes, 1998). The model is able to quantify the effect of different irrigation and drainage scenarios on crop yield. WAVES calculates actual crop evapotranspiration taking into account the effect of both soil water and salinity stress.

In terms of solute transport, WAVES does not consider the adsorption of solutes onto the soil matrix. In addition, the application of the model is limited by large number of soil and crop parameters. It requires 22 vegetation parameters to describe the canopy carbon balance, and interaction between soil and vegetation. Some of these parameters are difficult to obtain in practice (Zhang *et al.,* 1996). Table 4.1 presents a summary of the input parameters used for simulations with the WAVES model.

4.4.4 SWAP

The SWAP model includes a crop production function so that, it is able to assess crop yield response to water and salinity stress. In addition, SWAP can deal with several water management scenarios and their effect on crop yield. Irrigation scheduling in these scenarios can be considered as fixed or according to a number of criteria (Van Dam, 2000).

Ines *et al.,* (2001) identified the following limitations:

- The soil evaporation and crop transpiration are strongly dependent on the function describing Leaf Area Index (LAI).
- At low values of saturated hydraulic conductivity, the model fails to finish simulations, as the Richard's equation cannot be solved at these low values.

- The model does not account for the nonequilibrium sorption of pesticides.

Another limitation of the SWAP model is that it needs a lot of data that are not readily available in many areas of the world. Table 4.2 summarises the input data required by the model.

Table 4.1: Input variables and principle model parameters of WAVES

Data type	Description
Meteorological data	Total solar radiation, maximum daily temperature, minimum daily temperature, mean daily vapour pressure deficit, total daily precipitation.
Soil parameters	Soil albedo, soil roughness length, saturated hydraulic conductivity, volumetric moisture content at saturation, air-dry soil moisture content, capillary length scale, and shape parameters.
Vegetation parameters	Canopy albedo, rainfall interception coefficient, light extinction coefficient, specific leaf area, maximum assimilation rate of carbon, maximum plant available water potential, saturated light intensity, maximum rooting depth, canopy roughness length, residual stomatal conductance, slope parameters for conductance model, CO_2 mole fraction of the air, CO_2 compensation point, temperature when growth is optimum, temperature when growth is half optimum, leaf maintenance respiration coefficient, stem maintenance respiration coefficient, root maintenance respiration coefficient, leaf mortality coefficient, stem mortality coefficient, root mortality coefficient and vapour pressure coefficient.

Table 4.2: Summary of input data requirements for SWAP model

Kind of data	Description
Meteorological data	Daily global radiation, maximum and minimum temperature, average vapour pressure, average windspeed, total rainfall and reference evapotranspiration
Irrigation	Fixed irrigation: dates and depths, salt concentration in irrigation water, irrigation method Calculated irrigation; irrigation type, irrigation-timing criteria, irrigation depth criteria.
Crop	Crop rotation data, detailed crop growth, data required for the simple crop model
Soil	Soil water data, soil hydraulic parameters, and drainage data, bottom boundary conditions.
Heat	Heat flow data: data required for the analytical and numerical method
Solute	Diffusion, dispersion, solute uptake by roots, adsorption, decomposition, mobile and immobile water volumes, solute resistance in saturated zone

4.4.5 HYDRUS-2D and UNSATCHEM

HYDRUS-2D and UNSATCHEM are very closely related and can be alternates when crop yield simulation is not required. HYDRUS-2D is a more general solute transport code that includes non-linear adsorption and degradation. It is less sophisticated than UNSATCHEM in terms of some chemical transport functions. It is not limited to modelling a specific set of major ions. However, it cannot handle general cation exchange (MDH Engineering Solutions Corp., 2003).

HYDRUS-2D does not include any crop yield or growth modules. It does not account for the amount of solute added to the soil profile through irrigation water which affects on soil salinity simulation results. It cannot be used for long-term simulations, and it is limited to runs of one year duration.

4.4.6 SALTMED

Most of the developed models are one dimensional. The SALTMED model simulates water and solute transport in one or two dimensions and can be applied to any irrigation system as well as to rain fed agriculture. Other advantages of the model are (Ragab *et al.*, 2003):

(i) it accounts for the combined effect of water and salinity stress on crop transpiration, yield and subsequently on farmer's income;

(ii) it uses a water uptake function to account for vertical and horizontal root distribution; other models only accounts for the vertical distribution;

(iii) it is flexible and offers options depending on data availability and can be used in areas with poor data availability;

(iv) it can be used to predict long-term salinity impact;

(v) it includes a crop yield response function;

(vi) its interface is a menu based and as such it is relatively easy to use.

A shortcoming to the model is that, it solves the water and solute balances only for free draining soil or for the case of an impermeable lower boundary. It is not clear that the model can simulate interactions between a shallow water table and soil moisture movement. Certainly in the applications that there have been of the model, this has not been a problem, but it could be an issue in many applications where drainage is a significant part of the water management problem. It is interesting that the papers on SALTMED (Ragab, 2002; Ragab *et al.,* 2003; Ragab *et al.,* 2005) do not cite work on models such as SWAP or WAVES.

4.4.7 Significant Model Differences

From the above descriptions, the main differences between the models can be summarised as follows:

- potential crop evapotranspiration is computed in SWAP, WAVES and SALTMED models using Penman-Monteith equation (Monteith, 1981; Smith *et al.,* 1992; Allen *et al.,* 1998). In the other models ET_p is required as input. The WAVE model considers only the effect of water stress on crop transpiration and ignores the effect of salinity. Other models consider the combined effect of water and salinity stress on crop transpiration.
- the models differ in their ability of quantify the effect of water and salinity stress on crop yield (WAVE and HYDRUS-2D are the only models with no crop yield response functions). Other models use different crop yield response functions. UNSATCHEM and SALTMED are the only models that consider the cumulative

effect of water and salinity stress on crop yield using the additive function proposed by Stewart *et al.,* (1976) and Ragab, (2002), respectively. However, the UNSATCHEM model assumes that the sensitivity to water stress is the same during all growth stages.

- UNSATCHEM and HYDRUS-2D are the only models account for multi-component solute transport in variably saturated flow and their effect of crop transpiration and yield. Other models consider the transport of only one solute.
- the models differ in the required model data input; the SWAP and WAVES models require a large number of soil and crop parameters; some of these parameters are not readily available in many areas of the world.

Table 4.3 presents a summary of model characteristics.

Table 4.3: Comparison of the models in each of the five codes presented in this chapter.

Process	WAVE	UNSATCHEM	WAVES	SWAP	HYDRUS-2D	SALTMED
Variably saturated water flow	Finite difference model with one-dimensional unsaturated flow based on Richards' equation	Finite difference model with one-dimensional unsaturated flow based on Richards' equation	Finite difference model with one-dimensional unsaturated flow based on Richards' equation	Finite difference model with one-dimensional unsaturated flow based on Richards' equation	Finite difference model with two-dimensional unsaturated flow based on Richards' equation	Finite difference model with one-dimensional, two dimensional or three dimensional unsaturated flow based on Richards' equation
Root water uptake	Sink term in Richard's equation depends on water stress only.	Sink term in Richard's equation depends on osmotic stress and water stress.	Sink term in Richard's equation depends on osmotic stress and water stress.	Sink term in Richard's equation depends on osmotic stress and water stress.	Sink term in Richard's equation depends on osmotic stress and water stress.	Sink term in Richard's equation depends on osmotic stress and water stress.
Unsaturated hydraulic properties	van Genuchten (1980) model for $\theta(h)$ and different models for $K(h)$ or $K(\theta)$ (Gender 1985; Gilham *et al.*, 1976; Brooks and Corey, 1964; van Genuchten, 1980)	van Genuchten (1980) model with the capillary model of Mualem (1976) for both $\theta(h)$ and $K(h)$.	Broadbridge and White (1988) model for both $\theta(h)$ and $K(h)$	van Genuchten (1980) model with the capillary model of Mualem (1976) for both $\theta(h)$ and $K(h)$.	Brooks and Corey, 1964, van Genuchten, 1980 and Vogel and Cislerova, 1988 model for both $\theta(h)$ and $K(h)$	van Genuchten (1980) model with the capillary model of Mualem (1976) for both $\theta(h)$ and $K(h)$.
Initial and boundary conditions for the water flow system	Initial condition on pressure head; head and flux boundary conditions; ponding and seepage	Initial condition on pressure head; head and flux boundary conditions; ponding and seepage	Initial condition on pressure head; head and flux boundary conditions; ponding and seepage	Initial condition on pressure head; head and flux boundary conditions; ponding and seepage	Initial condition on pressure head; head and flux boundary conditions; ponding and seepage	Initial condition on pressure head; head and flux boundary conditions; ponding and seepage
Solute transport equations	One-dimensional, time varying; liquid and solid phases; 1st order decay; convection-dispersion equation; non equilibrium	One-dimensional, gas, liquid and solid phases; 0th order production, 1st order decay; advection-dispersion; equilibrium/non-equilibrium sorption. non linear sorption	One-dimensional advection-dispersion including equilibrium non-linear sorption; linear decay	One-dimensional advection-dispersion including equilibrium non-linear sorption; linear decay	Two-dimensional, gas, liquid and solid phases; 0th order production, 1st order decay; advection-dispersion; equilibrium/non-equilibrium sorption. non linear sorption.	One-dimensional, two dimensional or three dimensional, time varying; liquid and solid phases; 1st order decay; convection-dispersion equation; non equilibrium

Table 4.3 (contd.): Comparison of the models in each of the five codes presented in this chapter.

Process	WAVE	UNSATCHEM	WAVES	SWAP	HYDRUS-2D	SALTMED
Initial and boundary conditions for the solute transport	A flux type top boundary condition. The lower boundary condition is zero gradient at the bottom of the flow domain.	Initial conditions for liquid and solid phases; pressure head (Dirichelet condition) , flux (Neumann condition) or combination of two (Cauchy condition)	Concentration flux for both upper and bottom boundary conditions.	Initial conditions for liquid and solid phases; pressure head (Dirichelet condition) , flux (Neumann condition) or combination of two (Cauchy condition	Initial conditions for liquid and solid phases; pressure head (Dirichelet condition), flux (Neumann condition) or combination of two (Cauchy condition	Concentration flux for the upper boundary condition. Free drainage at the bottom of the profile is assumed otherwise an impermeable layer at the bottom is assumed.
Strengths	It can be modified without the need to change the structure or its input files, mechanistic model provide physics based modelling of soil moisture movement, it can deal with the upward capillary flux from watertable,	Deals with the reactive transport of multi-component solute and their effect on transpiration, simulates cation exchange reactions, considers the effect of chemistry on $K(h)$, includes crop yield response function	It is applicable in wide range of conditions, represents wide range of processes. It allows long-term of simulation. It includes crop yield response function.	It offers wide range of applications for irrigation water management. It includes crop yield response function.	It includes non-linear adsorption and degradation. It is not limited to a specific set of major ions.	It can be used in area with limited data availability. It accounts for the vertical and horizontal root distribution. It can be used to long-term salinity impact. It includes crop yield response function
Limitations	It is limited to application to one calendar year. Does not account for the effect of salinity stress on transpiration, does not include yield response function	Boundary conditions is complex, it cannot be used for long-term simulation, it does not consider the amount of solutes added to the soil through irrigation water, it is limited to modelling a specific set of major ions.	Solute is assumed to not adsorb on the soil matrix or affected by soil hydraulic properties or removed by the plant roots.	The model cannot finish simulation at low values of hydraulic conductivity. It needs a lot of input data	High computational demand, does not calculate potential evapotranspiration from climatic data. It cannot handle general cation exchange	It solves water and solute balances only for free draining soil. It doesn't account for the capillary rise from shallow water table

4.5 Model Applications

This section presents a brief review of applications of the above models to simulate water and solute transport in the unsaturated soil zone. Researchers worldwide have applied these models under different conditions, for different crops to simulate crop transpiration, deep percolation, crop growth response to different irrigation and drainage scenarios, and leaching of fertilisers and pesticides from soil. However, as the models were developed in the last ten years, the literature describing their application is not extensive.

4.5.1 Applications: Evapotranspiration

Fernandez *et al.*, (2002), successfully applied the WAVE model to predict soil moisture content and maize crop transpiration, under Mediterranean conditions. However, they found that the model was sensitive to the input values of leaf area index (LAI) and crop coefficient (K_C).

The WAVE model was successfully used by Meiresonne *et al.*, (1999) to simulate crop transpiration. However, they reported that further improvements to WAVE are required. In periods of high evaporative demand, when the model overestimated transpiration, a parameter should be introduced to account for the reduction in stomatal conductance caused by high values of radiation.

The WAVE and SECRETS (Sampson *et al.*, 2001) models were used by Meiresonne *et al.*, (2003) to simulate crop transpiration. Simulated transpiration was compared with transpiration measured by lysimeter. Results showed that, there was reasonable agreement in the annual water balance between the two models. However, SECRETS estimates of crop transpiration were closer to the measurements than those of the WAVE model. The WAVE model overestimated transpiration during periods of no rainfall and underestimated transpiration during rainfall. Both models estimated higher evapotranspiration than measured.

The WAVES model was tested by Zhang *et al.*, (1996). They found that the simulated evapotranspiration and soil moisture content agreed well with the observations. They concluded that the model can be used to assess the effect of irrigation management on crop growth.

Slavich *et al.,* (1998), tested the WAVES model to predict lucerne evapotranspiration under shallow water table conditions, and showed that modelled evapotranspiration rates agreed well with those observed over three growing seasons. They demonstrated that the model, with the current modelled processes of crop response to water stress and climatic conditions, gives an adequate prediction of crop transpiration and growth under the conditions of a shallow water table.

4.5.2 Applications: Irrigation Scheduling

D'haeze *et al.,* (2003), used the WAVE model to evaluate irrigation practices in Central Vietnam. They tested the crop growth response of *Coffea canephors* to different irrigation application depths. In comparison with observed data, the simulation results showed that the model can accurately simulate soil moisture content and can be used to assess the effect water stress on crop growth.

The WAVE model was linked to a crop yield response model by Mott MacDonald (2000b) to assess crop yield response to water and salinity stress and to waterlogging in South Kazakhstan. Modelling results indicated that acceptable yields of cotton could be achieved with an annual water application of 800 mm, accompanied by an annual drainage of 200 mm (Mott MacDonald, 2004).

The WAVE model was used successfully to simulate the effect of water supply capacity on crop growth in Netherlands (Verhagen *et al.,* 1995).

WAVES was used by Wang *et al.,* (2001) to simulate the long-term effect of irrigation management on crop growth in the North China Plain where there is competition for available irrigation water. They demonstrated that soil evaporation under a wheat canopy was high and accounted for about 30% of evapotranspiration, and that mulching could reduce soil evaporation by about 50% and save 80 mm of water during wheat growing season.

Kang *et al.,* (2003), successfully used the WAVES model to study the effect of different irrigation water application on crop yield and water use efficiency in China. They reported that appropriately used limited irrigation could improve crop yield and water use efficiency.

Droogers and Torabi (2002) used SWAP to study the effect of different irrigation applications and salinity levels on the yield of different crops under different soil types. They demonstrated that the SWAP model was able to provide a realistic assessment of the effect of wide range of irrigation scenarios on soil water and salinity levels, and subsequently on crop yield.

Qureshi *et al.,* (2002), used the SWAP model to assess the best irrigation depths and intervals for sugarcane production in Pakistan. A crop water production function (Doorenbos and Kassam, 1979) was used to predict yield and water use efficiency from model-predicted transpiration. It was found that the seasonal total of 1650 mm, applied at 15-day intervals was the best irrigation schedule for the region, and increased yield by about 76%.

The effect of water delivery schedules on crop production, water saving, soil salinity, drainage volumes and water table depth in Punjab, Pakistan, was evaluated by Sarwar *et al.,* (2001) using the SWAP model. They reported that maximum crop yield and water use efficiency could be obtained under the *On-demand schedule* in which farmers decide when and how much water should be applied according to the variation in rainfall and evaporative demand. Moreover, the *On-demand schedule* was effective in irrigation water saving, reducing drainage volumes, and deep percolation.

The HYDRUS-2D model was used by McKeering *et al.,* (2004) to evaluate the ability of alternative irrigation scenarios to create effective partial root zone deficit for cotton on cracking clay soils. They found that the accuracy of the model in predicting soil moisture was low due to difficulties and errors in parameterisation of the root water uptake and soil hydraulic properties. They reported that, it would be difficult to implement partial rootzone drying strategies on cracking clay soils for cotton production.

HYDRUS-2D was also used to simulate water movement and solute transport in soil and groundwater in New Zealand. The model simulated well the general trend of field observations for soil water content, and soil water potential. The simulation results were better for less heterogeneous soils (Pang *et al.,* 2000).

4.5.3 Applications: Salinisation

Smets *et al.,* (1997) calibrated and applied the SWAP model in the Punjab area of Pakistan to evaluate current irrigation practices as well as the impact of different irrigation practices on soil salinity and crop transpiration for cotton and wheat. They demonstrated that the irrigation interval is an important management option to control soil salinity and optimise transpiration. Irrigating sandy soils less frequently with larger application depths reduced transpiration but kept salinity at an acceptable level. Water application at the beginning of growing season also kept soil salinity under control. Long-term simulation for the current irrigation practices indicated that crop transpiration was lower in sandy soils than in loamy soils when the irrigation quantity was decreased. Salinity stress was more pronounced in loamy soil than in permeable sandy soils, and under-irrigation had a greater impact on salinity stress than the quality of irrigation water.

The SWAP model was applied by Singh (2004) to formulate guidelines for irrigating cotton and wheat crops with saline groundwater. The impact of irrigating with different depths and water qualities on crop performance and soil salinity was evaluated. The simulation results indicated that it was possible to achieve sustainable crop production with a total water application of 800 mm with EC values of up to 14 dS/m. However, it was found that leaching must be applied with water of good quality $(0.3-0.4\ dS/m)$. The implementation of these guidelines would greatly help in achieving sustainable crop yield by avoiding water logging and salinity problems.

Zhang *et al.,* (1999) studied the effect of a shallow saline water table on salt accumulation, evapotranspiration, ground water uptake and plant growth of lucerne in Griffith, NSW, Australia. It was found that the WAVES model was able to predict daily and seasonal variations in evapotranspiration, upward flux from the water table, plant growth in terms of leaf area development, soil salinity, and the root water extraction pattern. There was a considerable decline in transpiration, leaf area growth, and upward flux after groundwater salinity increased from 0.1 dS/m to 16 dS/m. According to these results, they suggested that the WAVES model is applicable to irrigated agricultural systems.

Utset and Borroto (2001) used the SWAP model to assess the effect of irrigation on water table level and subsequently on soil salinity at San Antonio del Sur Valley, in the southeast of Cuba. The simulation results showed that, increasing irrigation water caused a high water table and as a result, saline soil zones enlarged from 31.4 to 96.8 ha within a 15 year simulation period.

The SALTMED model has been used by Ragab *et al.,* (2005) with data for five growing seasons from Syria and Egypt, and successfully predicted the effect of salinity on crop yield, water uptake, soil moisture and salinity distribution. The results indicated that, a 7 dS/m irrigation water reduced tomato yield by 50%. A good simulation of salinity can help avoid salinity build up in the rootzone if used to determine leaching requirements. The results proved that the SALTMED model can be a useful tool in the management of water, crop and soil under field conditions.

The calibrated SALTMED model was applied by Flowers *et al.,* (2005) to study the effect of irrigation with saline water on tomato transpiration and yield using drip and furrow irrigation methods in Egypt and Syria. The irrigation treatments were: (a) the use of mixed saline and fresh water, blended in different ratios; and (b) the use of fresh water during the sensitive stages for salinity and saline water during the salinity tolerant stages. Results showed that, in Egypt, yield and fruit number were highest with the combination of drip irrigation and blended water. In Syria, yield under drip irrigation was also higher than that under furrow irrigation and decreased with increasing salinity of irrigation water. There was good agreement between simulated and observed transpiration and yield in Syria and Egypt over 3 years, confirming the applicability of the SALTMED model under saline conditions.

4.5.4 Applications: Solute Transport

Ducheyne *et al.*, (2001) used a calibrated and validated WAVE model to examine the factors affecting the amount of nitrate leached at the bottom of the rootzone. They reported that, the nitrate leached out of the soil profile is controlled by the fertiliser practice, the rainfall depth and distribution, soil texture and the past fertilisation practice.

The WAVE model has been applied to predict water and nitrogen status in the soil profile and their effect on crop growth (Vanclooster *et al.*, 1995), and to predict pesticide fate, transport and leaching (Vanclooster *et al.*, 2000a; Vanclooster *et al.*, 2000b). They reported that the potential of the model to accurately predict solute transport and pesticide fate is still limited, and that further developments in the model calibration and validation, including sensitivity analysis, were required in order to reduce the output uncertainty and improve its prediction accuracy. Verhagen *et al.*, (1995) applied the WAVE model to calculate nitrate leaching. They reported that the model can be used to estimate nitrate fluxes in soil which are a side effect of agricultural production system, and to simulate pesticide dynamics.

Kaledhonkar *et al.*, (2001) used the UNSATCHEM model to assess the effect of using alkaline irrigation water, and to understand the complicated chemical processes that affect solute transport in the soil under these conditions. There was a good agreement between simulated and observed ion concentrations. They reported that the model could be used for assessment of the effect of using alkaline irrigation water and in evaluating sodic soil reclamation.

Suarez, (2001) reported the successful use of the UNSATCHEM model to evaluate field reclamation of a sodic saline soil using gypsum or calcium. Electrical conductivity (EC) and sodium adsorption ratio (SAR) predicted by the model after reclamation fitted well with measurements.

Pang *et al.,* (2000) used HYDRUS-2D to simulate pesticide transport in soil and groundwater. The results showed that HYDRUS-2D simulated pesticide concentration in soil and groundwater were similar to the observed values.

Many other studies have successfully used the HYDRUS-2D model, to simulate pesticide transport in soils. Persicani (1996) reported that the HYDRUS-2D model is sensitive to the sorption parameter K_d and the degradation coefficient μ, the model needs proper input ranges for these parameters to obtain reasonable simulation of pesticide transport especially in highly sorptive soils. When calibrating the model with the best-fitted K_d value, the model predictions were appreciably improved.

The HYDRUS-2D model has also successfully been used to simulate chloride and nitrate transport in soil (de Vose *et al.,* 2002).

4.6 Conclusions

In this chapter, six unsaturated zone models for simulating water movement and solute transport have been described and discussed. All models presented have a similar conceptual basis and solve the same equations for simulating water and solute transport. WAVES and SWAP require a lot of input data, that are not always readily available. UNSATCHEM is the only model that accounts for multi-component solute transport with major ion equilibrium and kinetic chemistry in variably saturated flow, with ability to quantify crop yield response to water and salinity stress. However, it requires salinity data in terms of soluble, adsorbed and precipitated salts as input which is not always available.

The HYDRUS-2D model is limited in that it does not include crop production functions and is unable to quantify the effect of water and salinity stress on crop yield. It is not clear from the literature if the SALTMED model is capable of dealing a water table interface. It would appear that it can deal with a free drainage lower boundary or with an impermeable lower boundary, which by implication would result in build up of a saturated zone. There is not, however an ability to deal with controlled drainage, and this may limit its applicability.

When the research began, source codes access was only available for the WAVE model. The SWAP model code is now available, and in future research it would be of interest to evaluate this model also. The WAVE model was selected for use in this research, primarily because of source code access that would permit further model development with respect to incorporating the combined effects of water and salinity stress on actual evapotranspiration, and crop yield. In terms of input data requirements, WAVE requires lesser data on soil, crop and climatic data than other models. In addition, it provides physics based modelling of soil moisture movement, solute transport, and root development. It is able to assess the contribution from the water table through capillary flux in partially meeting crop water requirements. It is also able to assess the influence of the water table on the salinity levels in the root zone.

CHAPTER 5

The WAVE Model

5.1 Introduction

As indicated in Chapter 4, the WAVE model was selected to investigate water and solute transport in the vadose zone, and to assist in the evaluation of alternative water and salt management strategies in South Kazakhstan. A weakness of the WAVE model is that it calculates actual crop transpiration assuming that the crop is only under the effect of soil water stress. It does not take into account the combined effects of soil water stress and salinity on crop transpiration and this makes it less applicable under salinity conditions. To address this problem, the model requires additional stress coefficients to synthesise the combined effects of accumulated water and salinity stress on crop transpiration. In FAO Irrigation and Drainage Paper No. 56 (Allen *et al.,* 1998), approaches are outlined for calculating crop transpiration under the combined effects of water and salinity stress. As a part of the research described in this thesis, the effects of water and salinity stress on crop transpiration have incorporated in a modified WAVE model, called WAVE_MS.

The WAVE_MS model has been used to simulate soil water balances and to investigate long-term salinity build-up in soil root zone. The effects of salinity and soil water stress on actual crop transpiration and yield under different water management practices were investigated in order to identify strategies that maximise crop yield under water shortage and salinity conditions. A crop yield response model, C_YIELD (Mott MacDonald, 2000b) was used to translate water and salinity stress effects on transpiration into impacts on crop yield.

This chapter provides a summary of the WAVE model theory, the equations describing water and solute movement in the unsaturated soil, and describes the modifications that have been made to create WAVE_MS. Section 5.2 outlines the

WAVE model theory. Section 5.3 describes the input data required by the model. In section 5.4, the interfaces and programs created by Mott MacDonald (2000b) to permit multi-year model runs are described. Section 5.5 presents the modifications made under this research to create WAVE_MS. The chapter ends with the concluding remarks.

5.2 The WAVE Model Theory

5.2.1 General

A general description of the WAVE model has been given in Chapter 4. The model was selected for use in this research primarily because the source code of the model was available, and this permitted greater flexibility in how the model could be used and modified. Source code is in fact now available for the SWAP model also, but had not been at the commencement of this research. The following sections describe the WAVE model structure and data requirements.

5.2.2 Model Structure

The model consists of five modules (Figure 5.1). These modules are:

- WAT: the water transport module calculates the water balance in soil-plant system using the Richardson equation;
- SOL: the solute transport module calculates the solute balance in soil-plant system using the coupled convection-diffusion equation;
- HEAT: the heat transport module calculates the heat balance in the soil-plant system;
- NIT: the nitrogen fate module calculates the nitrogen balance in the soil-plant system;
- CROP: the crop growth module simulates the time course of the leaf area index, the accumulation of the dry matter of the different plant organs and the root length and root density extension rate.

The model is programmed in a modular way, which allows development and modification of the model by incorporating other modules without the need to adapt the model structure or the existing input files of the model. For the purposes of the present research, the HEAT, NIT and CROP modules were not used. The CROP module is focussed towards crop development, and it was considered that sufficient data would not be available to permit it to be applied to cotton in South Kazakhstan. The influence of salinity on crop development is not included, and this in itself was a significant limitation for the application intended under this research.

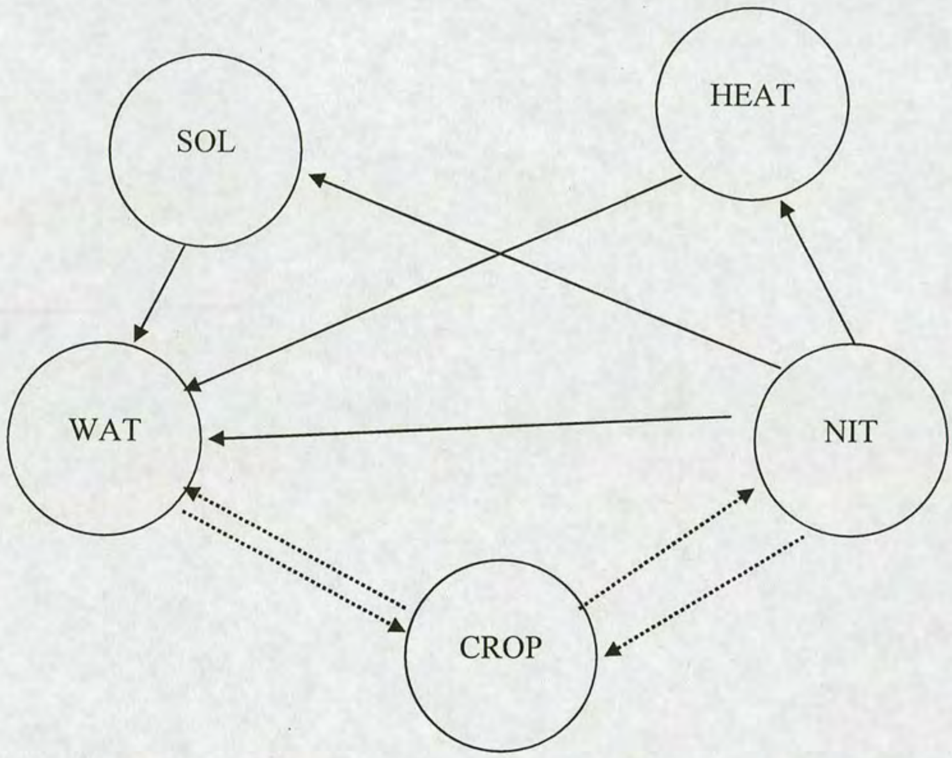


Figure 5.1: Schematic representation of the WAVE model modules. (Vanclooster *et al.,* 1994).

5.2.3 Space and time scales

WAVE describes water, solute, and energy fluxes in the vertical direction only. To reflect soil heterogeneity, the soil profile is split into a number of soil layers that have similar characteristics. These layers are then subdivided into equally sized intervals or compartments (Figure 5.2). The compartments form the basis of the finite difference discretisation used in solution of the water and solute transport equations. Nodes are considered to be at the centre of compartments (Vanclooster *et al.,* 1994).

The WAVE-model uses variable time steps. This limits mass balance errors in the water flow equation. Water transport, heat transport, solute transport, and solute transformations are simulated in time steps smaller than a day. For other processes a fixed daily time step is used.

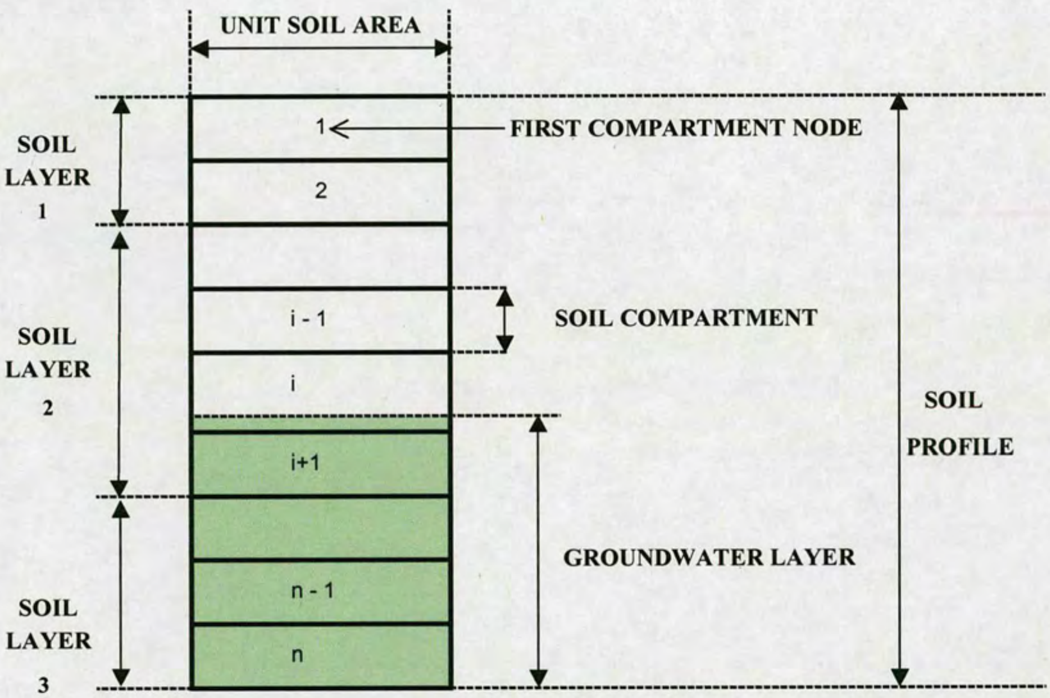


Figure 5.2 Concept of vertical space scale (Vanclooster *et al.,* 1994)

5.2.4 The Water Transport Module (WAT)

The soil water balance can be simply written as (Vanclooster *et al.,* 1994):

$$\Delta W = (P + I + U) - (R + E + D + T + Int) \qquad (5-1)$$

where, ΔW is the change in the soil water content (mm);

P is precipitation (mm);

U is the upward capillary into the soil root zone (mm);

I is the irrigation depth applied (mm);

R is the water depth lost by runoff (mm);

E is the actual evaporation (mm);

D is the percolation and drainage below the root zone (mm);

T is transpiration (mm);

Int is the interception (mm) which is varies with the crop and its stage of growth.

The model describes one-dimensional water transport using Richards equation. The Richards equation was presented in Chapter 4. To solve Richards equation, the soil moisture retention (MRC) and hydraulic conductivity (HCC) characteristics must be specified for each layer. Hysteresis in soil moisture retention can also be considered. The WAVE model uses the function proposed by van Genuchten (1980) to describe the moisture retention curve, which is the relationship between soil moisture content and pF, the pressure head as $\log_{10}\ cm$ of water (Vanclooster *et al.*, 1994). The van Genuchten (1980) function (described in Chapter 4) requires the saturated moisture content θ_s, residual moisture content θ_r, the inverse of the air entry α, and the constants m and n which define the shape of the curve. These parameters can be based on pedo transfer functions presented in the WAVE manual (Vanclooster *et al.*, 1994). The soil moisture retention parameters must be input for each layer. These parameters are extremely important in the model calibration, and can be refined to improve the model fit to observed soil moisture data.

It is necessary to define upper and lower boundary conditions in order to calculate the flux between soil compartments. The upper boundary condition is defined by specifying the minimum allowable pressure head at the soil surface and the maximum ponding depth. The lower boundary condition is defined by quantifying the flux at the bottom of the soil profile. In the WAVE model there are several options to define the bottom boundary condition (Vanclooster *et al.*, 1994). The options are as follows:

1. A groundwater table is present:

   (a) the groundwater level is specified as a function of time;

   or

   (b) the flux through the bottom of the soil profile is given as a function of time, the groundwater level is calculated;

   or

   (c) the flux through the bottom of the soil profile is calculated with a flux-groundwater relationship; the groundwater level is calculated.

2. The pressure head at the bottom of the soil profile is known as a function of time.

3. The flux through the bottom is known at each time step:

   (a) assumption of free drainage;

   or

   (b) zero flux.

4. Lysimeter with free outflow at the bottom.

5.2.5 Estimation of Potential Crop Evapotranspiration

The potential crop evapotranspiration (ET_C) is calculated in the WAVE model by multiplying the reference crop evapotranspiration (ET_o) by a crop coefficient (K_C) as described in the FAO Irrigation and Drainage Paper No. 24 (Doorenbos and Pruitt, 1977).

Potential crop transpiration (T_P) and potential soil evaporation (E_P) are calculated by splitting ET_C using the Leaf Area Index (LAI) (Vanclooster *et al.*, 1994):

$$E_P = e^{-0.6LAI}.ET_c \qquad (5-2)$$

$$T_P = ET_c - E_P - CanStor \qquad (5-3)$$

where, LAI is the leaf area index

E_P is the potential soil evaporation (mm/day);

T_P is the potential crop transpiration (mm/day);

ET_C is the potential crop evapotranspiration (mm/day);

$CanStor$ is the amount of water which has been intercepted and is now released from the crop canopy (mm)

For each soil compartment, the root water uptake is computed by multiplying the maximum root water uptake ($S_{\max}$) with the reduction factor $\alpha(h)$, which is based on the pressure head (h). The WAVE model provides linear and hyperbolic relationship between $\alpha(h)$ and the pressure head. The wilting point value ($h_3 = -16000\ cm$, $pF = 4.2$) is often taken as the lower limit of this relationship. Root water uptake at different depths is determined by integrating the root water uptake term from the soil surface to an increasing depth z less or equal to the rooting depth L_r, until the integral becomes equal to the potential transpiration rate. If the integration over the complete rooting depth is insufficient to explain the potential transpiration rate, water stress is considered to occur. The actual transpiration rate is calculated as (Vanclooster *et al.,* 1994):

$$T_a = \int_0^{z \prec L_r} S(h,z)\,dz \le T_P \qquad (5-4)$$

where, T_a is the actual transpiration rate (mm/day)

T_P is the potential transpiration rate (mm/day)

L_r is the rooting depth (mm)

The WAVE model considers only the effect of water stress on crop transpiration.

5.2.6 The Solute Transport Module (SOL)

The model accounts for non-equilibrium solute transport, assuming convection-dispersion flow in the mobile soil region together with rate-limited exchange between the mobile and immobile soil regions. In both regions, adsorption is assumed to occur reversibly and linearly. Transport of solute in the mobile soil region is determined by chemical diffusion, convection-dispersion and hydrodynamic dispersion. The interaction between the two regions is expressed by adsorption and diffusion between both regions. The convection-dispersion equation is presented in Chapter 4.

The solute transport equation has many input parameters. These include; the distribution coefficient of an adsorbing solute (K_d), the chemical diffusion coefficient of the solute (Dif), empirical coefficients (a) and (b) relating the chemical diffusion in a pure liquid with diffusion in the soil medium, the soil hydrodynamic dispersivity (λ), the fraction mobile to total water content (θ_m / θ), the mass transfer coefficient between mobile and immobile soil zones (α) and the fraction of the adsorption sites in the mobile zone (f). These parameters need to be specified for each soil layer. K_d is one of the most important parameters in soil salinity calibration as it significantly effects the rate of salinity build up. This parameter controls the adsorption process of solutes in the soil complex. For linear and reversible adsorbing species, the distribution constant is used to relate solute in the soil solution and on the sorption sites as (Vanclooster *et al.*, 1994):

$$C_{sm} = K_d . C_m \qquad (5-5)$$

where, C_{sm} is the adsorbed solute mass on the soil complex $(Kg\ Kg^{-1}\ dry\ soil)$

C_m is the solute concentration in the mobile soil region $(Kg\ m^{-1})$

In solute transport the WAVE model uses a flux type top boundary condition (Vanclooster *et al.,* 1994):

$$J_s = C_f . q_w \qquad \text{for } q_w < 0.0 \text{ (infiltration)}$$
$$J_s = 0 \qquad \text{for } q_w > 0.0 \text{ (evaporation)} \qquad (5-6)$$

where, C_f is the solute flux concentration $(Kg\ m^{-3})$

J_s is the solute mass flux $(Kg\ m^{-2}\ s^{-1})$

q_w is the Darcian water flux $(m^3\ m^{-2}\ day^{-1})$

The lower boundary condition is a zero concentration gradient at the bottom of the flow domain.

5.3 Model Inputs

In its standard form, the WAVE model requires four data files (Vanclooster *et al.,* 1994):

CLIMDATA.IN: contains daily climatic data: precipitation, evapotranspiration and water applications (irrigation and leaching);

GENDATA.IN contains general information: number of soil layers with different characteristics, number of soil compartment in each layer and the bulk density of each layer;

SOLDATA.IN contains additional input for modelling solute transport in soil-plant system;

WATDATA.IN contains input required for modelling soil water flow: moisture retention characteristics and hydraulic conductivity in each layer.

A summary of particular data requirements is given in Table 5.1.

Table 5.1: WAVE model input parameters

CLASS	PARAMETERS AND INPUT VARIABLES
Climatic	Precipitation, evapotranspiration, water applications
Soil Hydraulics	Saturated and residual volumetric moisture content, inverse air entry value, shape parameters required by van Genuchten equation, saturated hydraulic conductivity and fitting parameters of the hydraulic conductivity model.
Plant water uptake	Potential evapotranspiration, crop coefficient and pressure head values required for the water stress reduction function.
Water bottom boundary	Water flux or pressure head at the bottom of the soil profile.
Water initial values	Soil moisture content or pressure head.
Soil solute transport	Chemical diffusion coefficient of solute in pure water, soil hydrodynamic dispersivity, parameters relating soil chemical diffusion coefficient to diffusion in water, mobile water content ratio, mass transfer coefficient, bulk density and the fraction of the sorption site in the mobile soil region.
Solute top boundary	Application rate of the solutes.
Crop growth	Number of seedling per area, leaf area development rate during plant juvenile stage, base temperature for juvenile growth, specific leaf area; maximum CO_2 assimilation rate, initial light use efficiency, light extinction coefficient, light scattering coefficient, maintenance factor for storage organs, assimilation requirement for dry matter conversion to storage organs, initial leaf area, etc.

5.4 The WAVE Model Interfaces and Utilities

5.4.1 Introduction

Mott MacDonald (2000b) developed a number of programs to operate with the WAVE model that permitted it to be used for multi-year simulations, and provided outputs that were more suitable for evaluating sustainable crop production under different water management strategies. They developed a crop yield response model to run with the output data on evapotranspiration and salinity produced by the WAVE model, and also developed a user interface that made the model easier to use, and errors in input data less likely. Graphical post-processing routines were also developed. In this section these interfaces and utilities are described.

5.4.2 The C_YIELD Model

The WAVE model is unable to quantify the impact of water supply, rootzone salinity, and root zone water logging on crop yield response, as it does not include any crop yield response function. The model was improved by linking a crop yield response function to it through a computer programme called C_YIELD. C_YIELD (Mott MacDonald, 2000b) was developed at the University of Edinburgh to read actual crop transpiration and soil salinity data from the WAVE model outputs and to calculate the impact of water shortage, root zone salinity and root zone water logging on crop yield response. It prepares a table of time series results, as well as summary results.

The C_YIELD program calculates the relative yield response to water stress, soil salinity and water logging in each growth stage using separate functions for each. The total relative yield is the product of the relative yields from the three functions.

Many water production functions have been developed and used to predict crop yield response to water stress. C_YIELD uses the multiplicative function proposed by Rao *et al.,* (1988). Discussion of yield response to water functions was presented in Chapter 3.

Under standard conditions, crop yield can be obtained at its potential level until some threshold electrical conductivity EC_e (electrical conductivity of saturated soil extract) is reached. Threshold EC_e values vary with crop type and variety. Very few yield response to salinity models are described in literature. The yield response to salinity in the C_YIELD program is based on the approach presented by Maas and Hoffman (1977) in which the crop yield linearly decrease as the EC_e value increase above the threshold soil electrical conductivity (A_S). The approach also requires the rate at which relative crop yield declines with increasing salinity (B_S).

The Maas and Hoffman approach is recommended in FAO Irrigation and Drainage Paper 56 (Allen *et al.,* 1998), and was described in Chapter 2. The relationship between yield and salinity is shown in Figure 5.3 below:

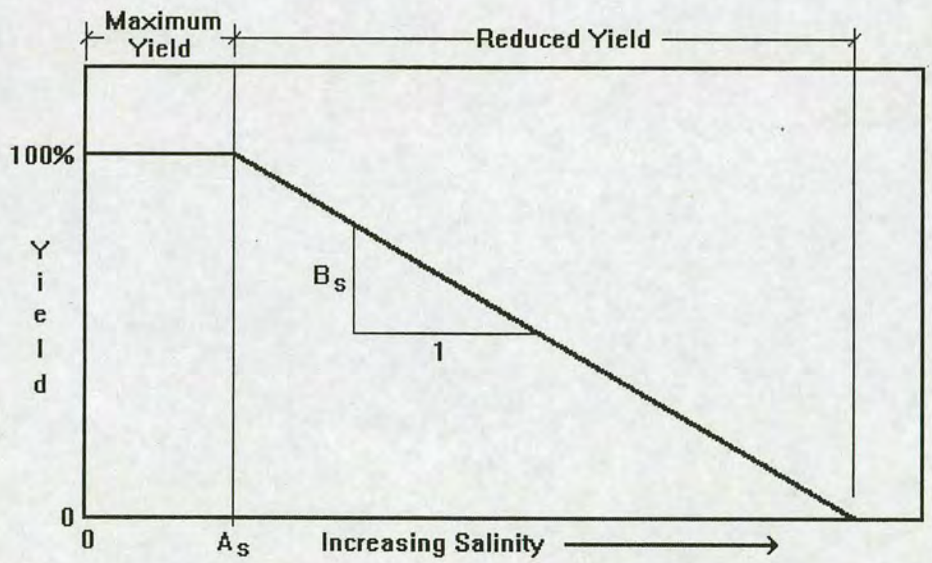


Figure 5.3: Simple relationship between yield and salinity (Mass and Hoffman, 1977)

The WAVE model produces an output file containing daily simulated soil salinity in each layer in mg/m^2. It was necessary to relate this to electrical conductivity EC_e in order to permit the effect of salinity stress on crop yield to be evaluated. As part of the field programme carried out by Mott MacDonald, soil samples were taken regularly, and soil salinity (% *dry solids*) and electrical conductivity (dS/m) were measured for each sample. The following relationship between EC_e and soil salinity % has been established by Mott MacDonald, (2003b):

$$EC_e = 1640 * TDS + 4.25 \qquad (5-7)$$

where, TDS is the percentage of salts in the soil (by weight).

EC_e is the electrical conductivity of the soil extract (mS/m)

According to this relationship, cotton will be under salinity stress with a salt concentration of about 0.47 %. Figure 5.4 presents the relationship EC_e and soil salinity.

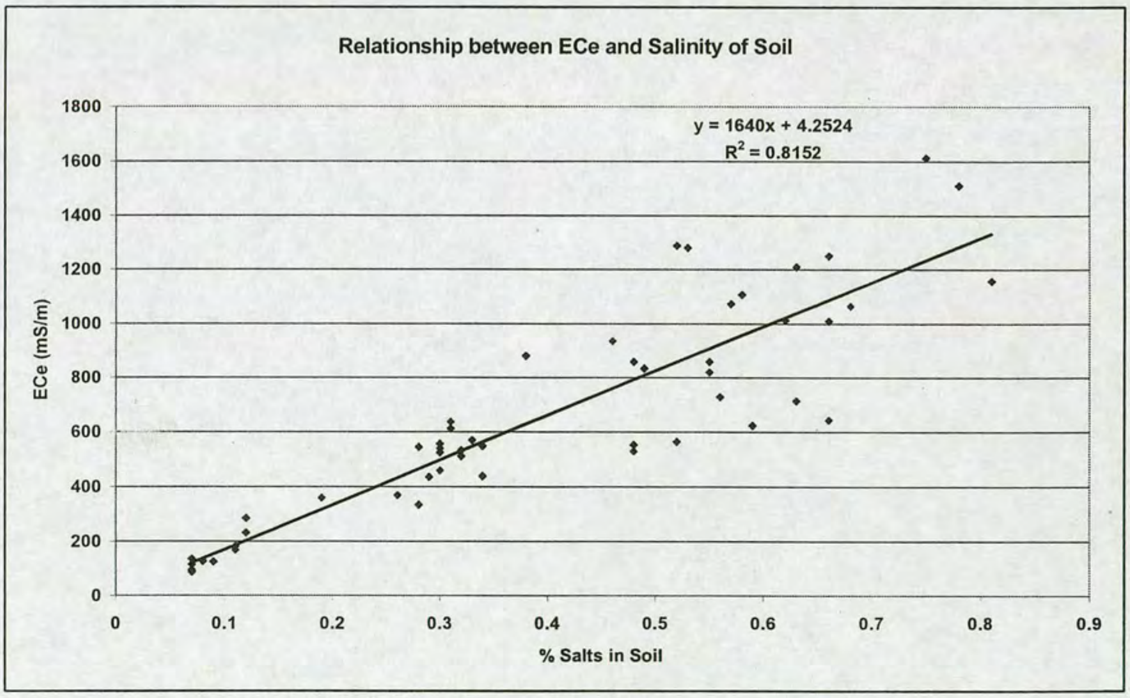


Figure 5.4: Relationship between ECe and soil salinity (Mott MacDonald, 2003b)

Water logging occurs when the soil pores in the root zone are filled with water and the roots become asphyxiated. It can severely restrict crop growth; in extreme cases crops die due to lack of oxygen in the root system. C_YIELD uses a very simple relationship in which potential yield is reduced by the proportion of the rooting depth that is saturated. It is also multiplicative between time steps.

The C_YIELD program requires two data files in addition to the files either used or created by WAVE. These are CROP_CHAR.DAT, which contains the crop characteristics, and SOIL_STRUCT.DAT. The contents of these files are indicated in Tables 5.2 and 5.3 respectively.

Table 5.2 Contents of the CROP_CHAR.DAT file

Data line	Description
Cotton crop characteristics	Single line title
4	Number of growth stages for crop
20,50,60,55	Length of each growth stage (days)
0.20, 0.55, 0.45, 0.20	Yield response factor for each stage
7.7, 5.2	ECe threshold value & the parameter (b) in equation (2-8).
15, 4, 1990	Planting date

Table 5.3 Contents of SOIL_STRUCT.DAT

Data line	Description
Birlik_P3	Title line
5, 100.0	No of soil layers and compartment size
2, 2, 2, 4, 50	No of compartments per layer
1640.0 4.25	constants in the EC_e – TDS relationship
1.40, 1.68, 1.46, 1.46	Soil bulk density for each layer

5.4.3 Pre-processing

The WAVE model is limited to application to a single calendar year at a time. This is a significant limitation when evaluating the effect of irrigation and drainage management practices on salinity build up, where it can take many years for the effect of any particular water management practise to become apparent, or to significantly reduce crop yield. To address this limitation a number of computer programs were written that permit it to be used in time series runs of up to 26 years (1990-2015). The storage levels and variable values from the end of one year's simulation are in effect input as starting conditions for the next year (Mott MacDonald, 2003d).

The data input files WATDATA.IN, and SOLDATA.IN (described above in section 5.3) need to be updated with configuration data for any particular model run. The GENDATA.IN and CLIMDATA.IN files are configured for individual years and base files are created initially for each year of the run. Further data on crop characteristics (K_C factors, LAI values and rooting depths during the growing season) are contained crop files called COTTON_CHAR.DAT and ALFALFA_CHAR.DAT. Appropriate values are copied from these files into the WATDATA.IN file (Mott MacDonald, 2003d). The file manipulations are managed through a series of DOS command files that are created at run time from the pre-processing interface.

Pre- and post-processing routines were developed that enable the WAVE model and C_YIELD to be from a Windows based menu system. This simpified operation of the model and made parameter modification much simpler and less error prone. Input data and parameters that are varied between model runs (irrigation and leaching applications, drainage conditions, soil and crop characteristics etc) are displayed through the interface and are stored in a data file with the extension CFG (for configuration).

The data required by the WAVE model can be considered under three categories: soil data, groundwater data, and cropping and irrigation data. These are described below:

i) Soil data

Part of the soil data input screen is shown in Figure 5.5.

- **Rainfall and Climate data set.** This includes daily potential evapotranspiration and precipitation. The pre-processor was set up with 13 years of historic data (1990 to 2002) from the Lenina weather station, which lies in the centre of the project area and was considered to be a representative station for the WRMLIP project area as a whole. The data sequence was simply repeated for the years 2003 to 2015, which permitted the model to be run for 26 years (1990 – 2015).

- **Soil type selection:** The user can choose between up to four sets of different base soil data files (A, B, C or D).
- **Average surface water salinity:** This is the average annual salinity of water in the Doystik Canal, which provides the project area with water for irrigation. Monthly adjustments may be required to reflect the monthly variations in the irrigation water salinity. In South Kazakhstan, an average surface water salinity of 1000 mg/l has been used for the model runs.
- **EC_FACT1 and EC_FACT2:** These parameters are required to describe the relationship between the electrical conductivity of a saturated soil extract, EC_e, and soil salinity expressed as a percentage of dry solids.
- **Soil layers:** A maximum of 10 layers can be used in the model.
- **Compartment size:** The maximum total number of compartments that can be used is 100. For the purpose of this research, a compartment size of 100 mm has been used throughout.
- **Salinity:** Starting salinity values $(\%\ dry\ solids)$, as this unit is the common method of expressing soil salinity in Kazakhstan. Soil salinity data used in the model runs in this research were obtained from the data collection report (Mott MacDonald, 2003a) which presents field data collected at three pilot areas in the Makhtaaral region of South Kazakhstan.
- **Bulk Density** $(tonnes/m^3)$. This parameter was provided by the data collection programme in WRMLIP for a number of sampling locations in each of the pilot areas.
- **Dispersion Coefficient.** This parameter controls the dispersion of solutes in the soil profile.
- **Residual Soil Moisture.** Is soil moisture content (%) at permanent wilting point.
- **Saturated Soil Moisture.** Is soil moisture content (%) at saturation, which has been taken as the measured porosity at all locations.

- **Alpha.** Is a required parameter for the van Genuchten (1980) equation, used to model soil moisture retention curve. This parameter has been defined from analysis of field data in each pilot area (Mott MacDonald, 2002). It has a great effect on the simulated soil moisture content and can be refined for particular locations in the calibration processes.
- **N and M.** Are further parameters in the soil moisture retention equation and they also important for calibrating soil moisture content.
- **Terminal Infiltration.** (m/day). Is the terminal infiltration rate for the soil in a particular layer. Initial values were obtained from field measurements, but may be calibrated.
- **Inf. P1 and Inf. P2.** Are parameters required by the Gardener hydraulic conductivity model and must be calibrated.

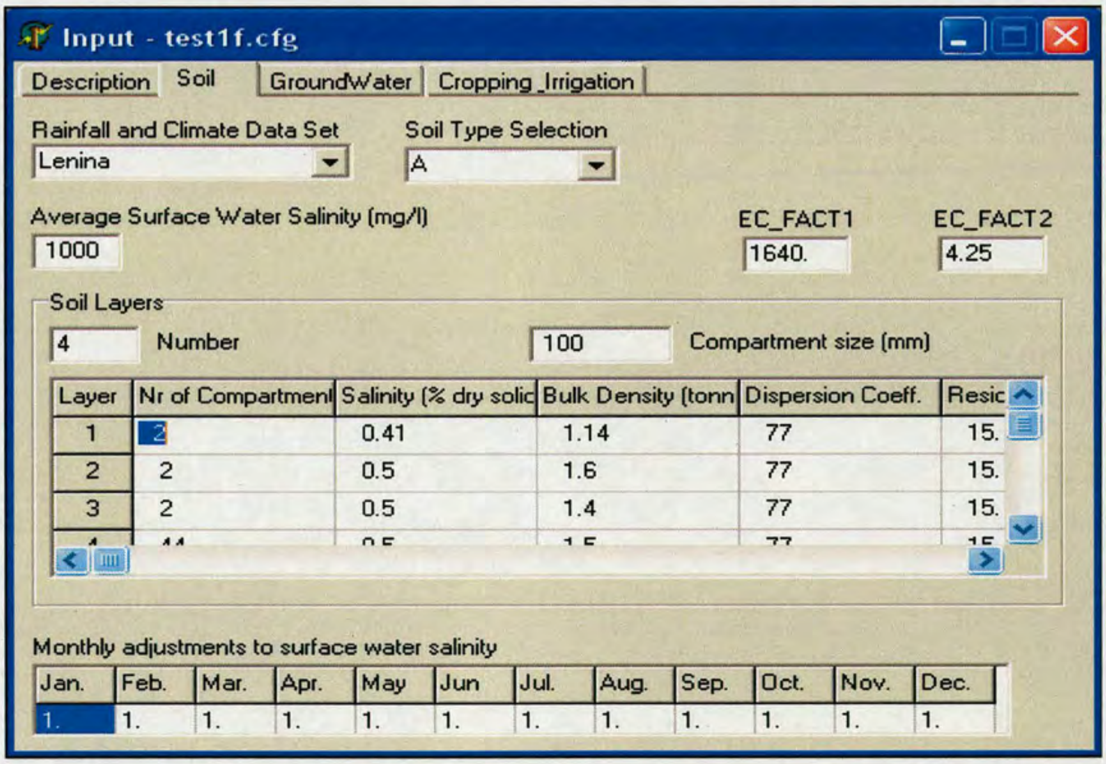


Figure 5.5: The data input / editing screen: Soil data

ii) Groundwater data

The groundwater data input screen is shown in Figure 5.6.

- **Starting Groundwater Depth (m).** The depth to the water table at the start of the simulation.
- **Level control.** If the model is run with groundwater level control, then end of month groundwater levels must be specified for each month of the run. This option is used mainly for calibration purposes when observed groundwater levels are available. When level control is selected, the drainage flux rate parameter boxes are greyed out.
- **Drainage flux rate parameters.** A1 and A2 can be used to calculate flux across the bottom boundary of the model as a function of groundwater level:

$$Q_b = A_1 . e^{A_2 \phi} \qquad (5-8)$$

where, A_1 and A_2 are the drainage parameters.

ϕ is the groundwater level (m)

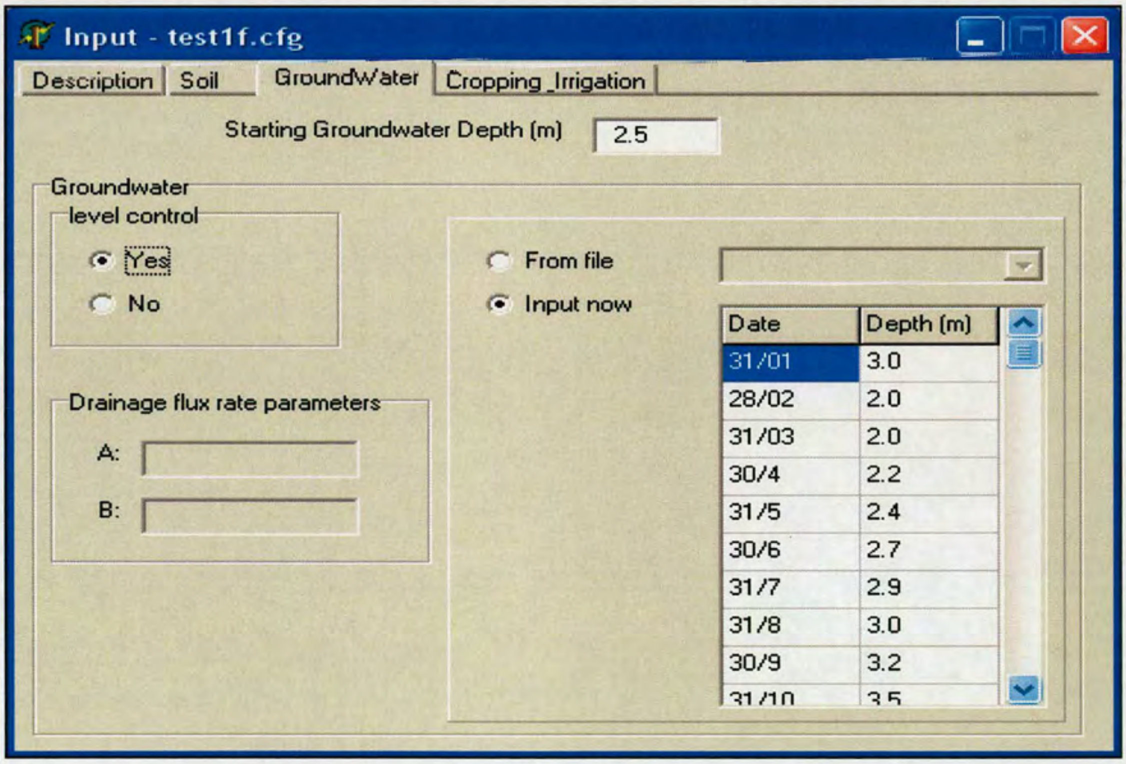


Figure 5.6: The data input / editing screen: Groundwater data

iii) Crop and irrigation data

The crop and irrigation data input screen is shown in Figure 5.7.

- **Crop.** The only crops available at present are cotton or alfalfa.
- **Leaching Applications.** The number, date (*day / month*) and depth (*mm*) of leaching applications are specified.
- **Planting Date.** Is the date (*day / month*) of planting.
- **Irrigation Applications.** The number, date (*day / month*) and depth of irrigation are specified.

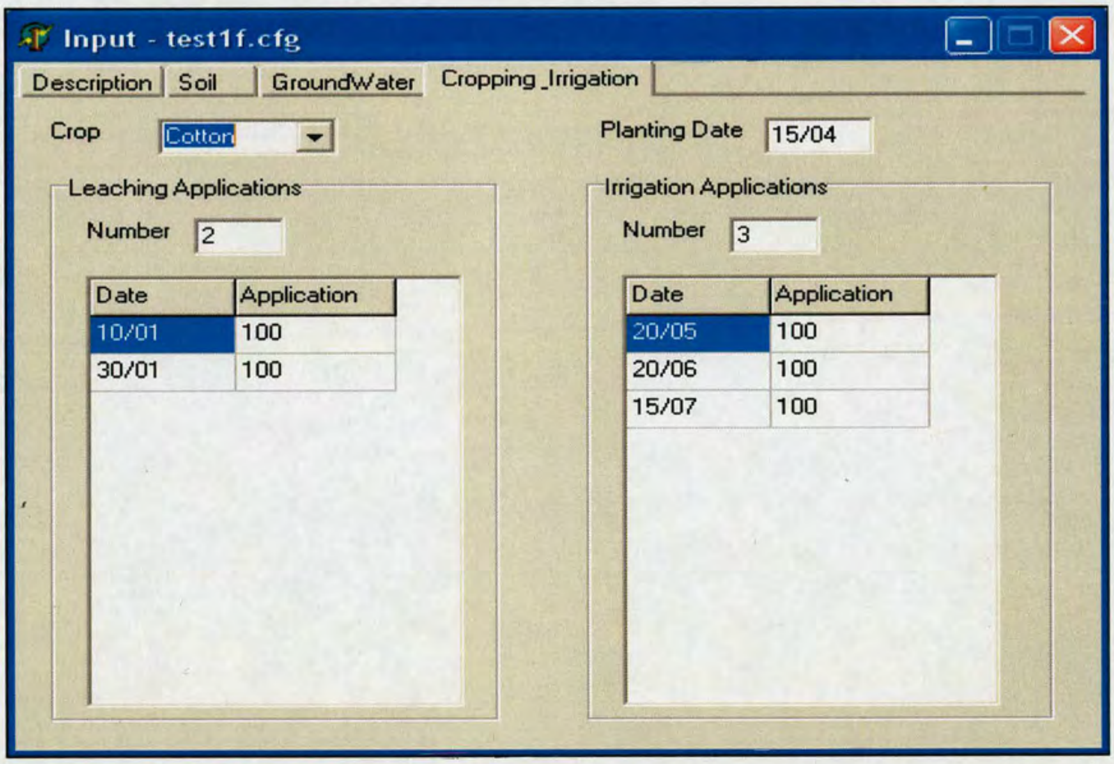


Figure 5.7: The data input / editing screen: Crop and irrigation data

5.4.4 Post-Processing

Post processing routines for the model were developed to extract data from the WAVE model outputs and prepare tables of time series results in a file called WAVE_PLOT.OUT containing the following daily data:

- Rainfall (*mm*)
- Irrigation (*mm*)
- Rootzone moisture content (%)
- Root depth (*mm*)
- Rootzone salinity (% *dry solids*)
- Potential evapotranspiration (*mm*)
- Actual evapotranspiration (*mm*)
- Cumulative evapotranspiration deficit (*mm*)
- Groundwater level (*mm*)
- Soil moisture by layer (%)
- Soil salinity by layer (% *dry solids*)
- Water flux at the bottom of the profile (*mm*)
- Solute flux at the bottom of the profile ($mg\ m^{-1}$)

C_YIELD produces from this a table of yield reductions due to water stress, salinity stress and water logging in a file called YIELD.OUT, which contains the following data:

- Stage of growth
- Crop reduction factor
- Actual crop evapotranspiration by stage
- Potential crop evapotranspiration by stage
- Yield response to water
- Yield response to salinity
- Yield response to water logging
- The overall crop yield

The model interface provides a series of options in the view results screen. The view result screen is shown in Figure 5.8. Graphical presentations of the following are available:

i) Salinity in the root zone

ii) Salinity by soil layer

iii) Soil moisture in the root zone

iv) Soil moisture by layer

v) Depth to water table

vi) ET_C and ET_a

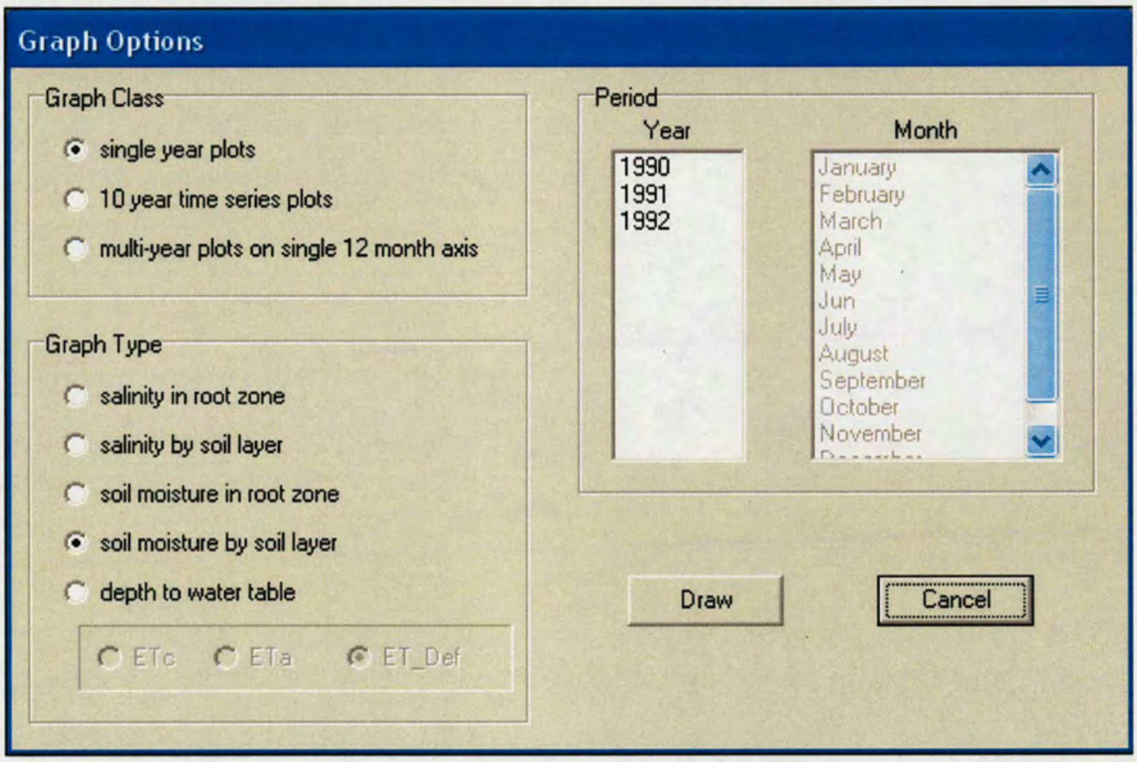


Figure 5.8: The view results screen

5.5 The Modified WAVE Model – WAVE_MS

The WAVE model is capable of dealing with the effect of soil water stress on crop transpiration. Fernandez *et al.* (2002) and Meiresonne *et al.* (1999) report that in terms of crop transpiration, the approach adopted by the original model works well under water shortage conditions. However, it is not able to take into account the effect of salinity on potential evapotranspiration. This restricts WAVE model application in arid and semi-arid conditions where water shortage and salinity are significant problems. Considering the effects of salinity is important, as the combined effect of water and salinity stress reduces crop transpiration and result in yield reduction. The higher the water stress and salinity, the lower the crop transpiration and yield. Where salinity stress exists and crop transpiration is reduced as a result of this, there will be impacts on soil moisture storage also, and water stress may be lower than would occur in the absence of salinity stress.

It was considered important that the WAVE model be improved to deal with the combined effect of soil water and salinity stress on crop transpiration. In order to achieve this, as part of this research the calculation of the actual crop transpiration (actual root water extraction rate) in the water transport module was modified to incorporate the effect of salinity on crop transpiration following the approach outlined in the FAO Irrigation and Drainage Paper No. 56 (Allen *et al.,* 1998). This included:

- modifications in the subroutine WAT_UPT.FOR to calculate crop transpiration reduction factors. The steps required to achieve this were:

  (a) Converting soil salinity units from mg/m^2 to $\%$ by weight of dry solids:

  $$Salt\_Conc = (TCSOLO \,/\, (Bulk\_Dens * 1.0E6 * DX)) * (1.0 - KDS) * 100 \qquad (5-9)$$

  where, $Salt\_Conc$ is the soil salinity ($\%$ *dry solids*),

  $TCSOLO$ is the soil salinity (mg/m^2),

  $Bulk\_Dens$ is the soil bulk density ($tonne/m^3$),

  DX is the compartment size (mm),

  KDS is the linear distribution parameter.

  (b) Converting soil salinity units from $\%$ by weight of dry solids to electrical conductivity (mS/m) according to equation $(5-7)$.

  (c) Incorporating the FAO approach (Allen *et al.,* 1998):

  $$ET_C = K_S.K_C.ET_o$$

  $$K_S = 1 - \frac{b}{K_y 100}\left(EC_e - EC_{ethreshold}\right)$$

where,

EC_e	is the mean electrical conductivity of the saturation extract for the root zone ($dS\ m^{-1}$)
$EC_{ethreshold}$	is the electrical conductivity of the saturation extract when yield starts to become affected by salinity
K_y	is a yield response factor
b	is the reduction in yield per increase in EC_e ($\% / (dS\ m^{-1})$)

The source code of the subroutine in which the actual crop transpiration functions were modified by incorporating the affect of salinity on crop transpiration is given in Appendix A.

- creating a new input file for the parameters required by the new concepts incorporated;
- modifications in the water balance module to incorporate a new subroutine (CROP_CHAR.FOR) to read the additional input data. The source code for the new subroutine is given in Appendix B.

The additional input parameters required for the calculation of the salinity reduction factor are:

- the electrical conductivity threshold value above which crop yield starts to become affected by salinity;
- yield response factors for the different growth stages;
- the reduction in yield per increase in the electrical conductivity of the soil extract.

The CROP_CHAR.DAT file is used by the WAVE_MS model to provide the above parameters.

There were no field data on actual crop transpiration from the WRMLIP project that would permit direct evaluation of the new functions in WAVE_MS. In addition, no experimental data on crop transpiration under soil water and salinity stress could be found in the literature with which to evaluate the performance of WAVE_MS. Qualitative evaluation of the revised model could only be made by comparing results produced by WAVE_MS with those produced by the original model. Actual crop transpiration computed using the WAVE_MS model should be lower than computed using the original version of WAVE when the EC_e exceeds the threshold value. This in turn affects the simulated soil moisture in the rootzone as well as simulated groundwater level, which should be higher than those simulated by the original model.

In order to test the modifications, 11-year simulation runs were carried out with the original and modified versions of the model. A cotton crop was used, with inadequate irrigation and drainage. The model was set up with three irrigation applications of 100 mm each in May, June and July, and two leaching applications of 100 mm each in January and February. The irrigation and leaching water were assumed to have a solute concentration of 1360 mg/l. There was no groundwater or solute flux out of the lower boundary of the model by deep percolation. The salinity build up was quite dramatic over the simulation period (1990-2000) but it did not exceed the threshold value (7.7 dS/m for cotton) for the first five years of simulation (1990-1994). As a result, actual daily cotton transpiration as simulated using WAVE_MS and WAVE was exactly the same for this period (Figure 5.9). The daily ET_a simulated using WAVE_MS was lower than the ET_a simulated using the original model for the period 1995-2000 because the soil salinity exceeded the threshold value in this period. Figure 5.10 shows the reduction in cotton transpiration due to salinity stress for the 1999 calendar year. The time series of annual cotton transpiration simulated using both versions is shown in Figure 5.11. Clearly the cumulative salinity build up is influencing actual evapotranspiration.

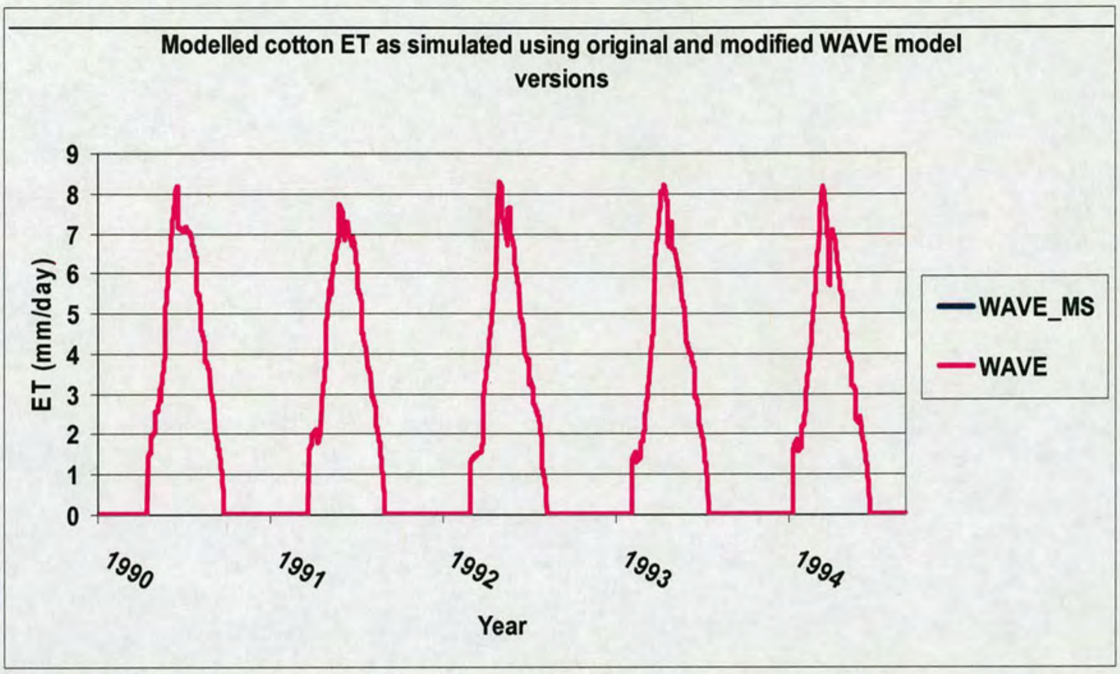


Figure 5.9: Modelled cotton ET using original and modified WAVE model versions (1990-1994)

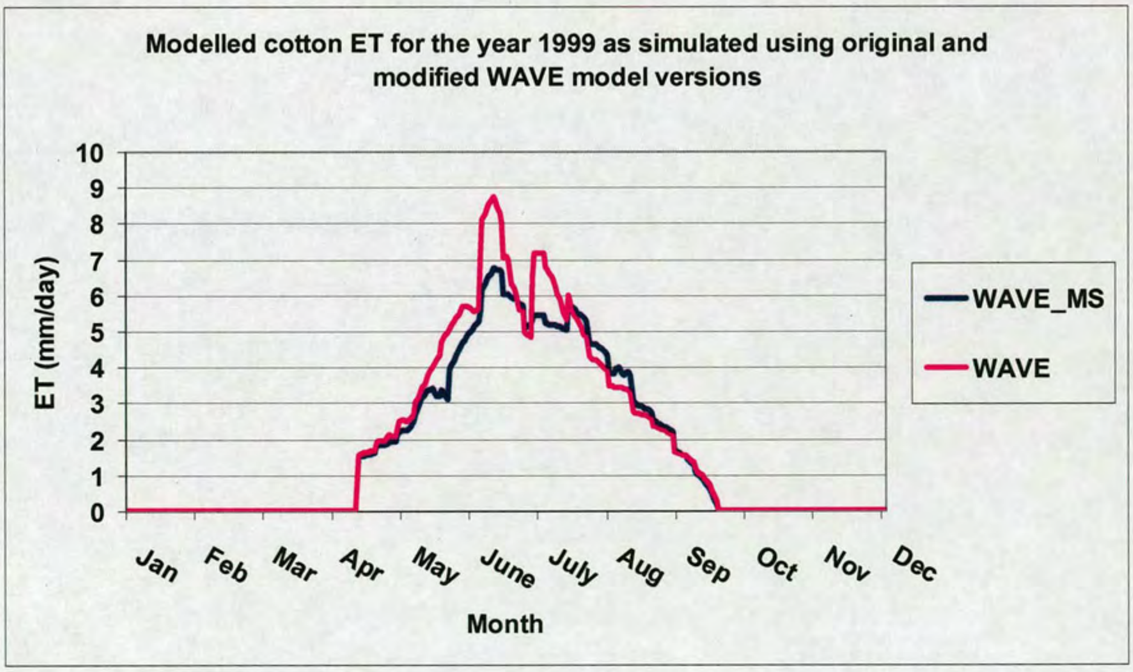


Figure 5.10: Modelled cotton ET using original and modified WAVE model versions (1999)

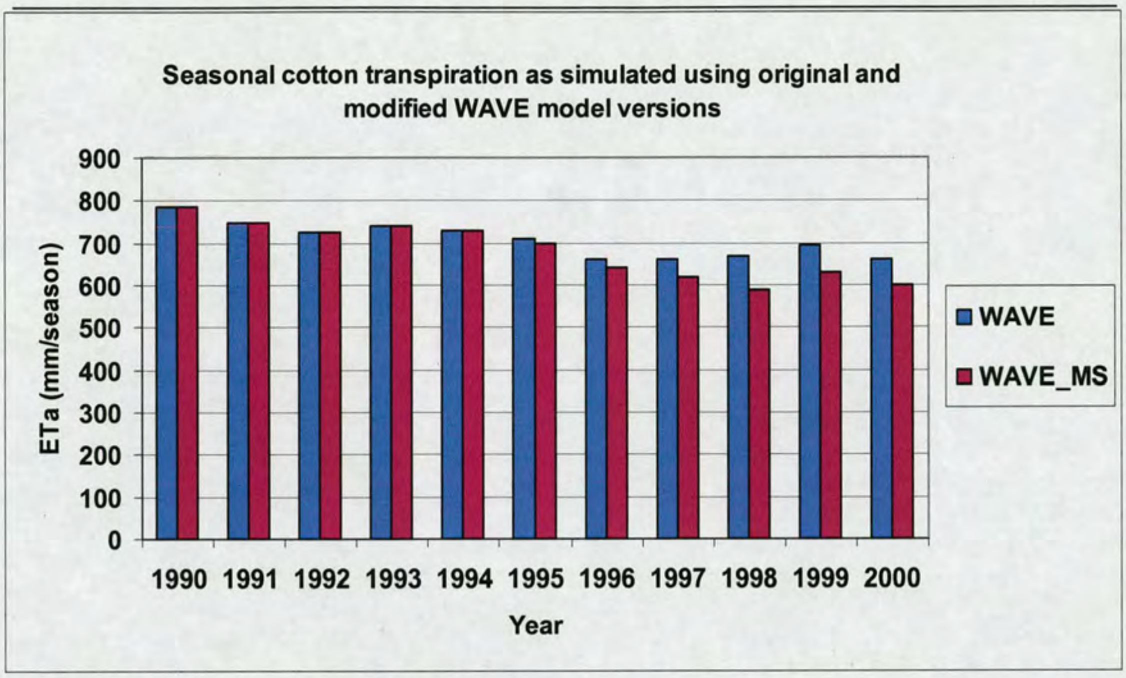


Figure 5.11: Seasonal cotton transpiration using original and modified WAVE model versions (1990-2000)

With a reduction in simulated actual evapotranspiration, root zone soil moisture content simulated by the WAVE_MS model was higher than that simulated using the original version. The difference in the root zone soil moisture between the two versions increased as the effect of salinity on transpiration in the modified version increased. For the period 1990-1994 there was no difference in root zone soil moisture between the two versions (Figure 5.12). Figure 5.13 shows simulated soil moisture for the 1995-2000 period.

Simulated groundwater levels are also affected by changes in actual evapotranspiration. With reduced evapotranspiration there is increased groundwater recharge and higher groundwater levels. Figure 5.14 shows groundwater depths simulated with both versions of the model. Higher groundwater levels (lower depth to water table) result in the 1995-2000 period.

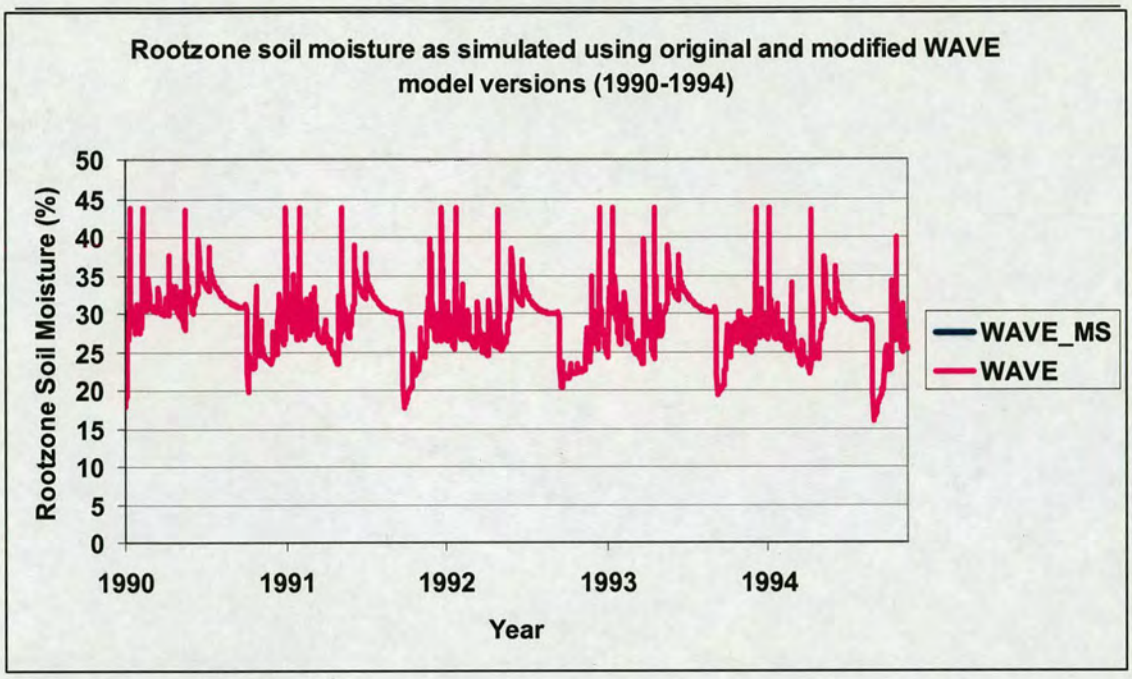


Figure 5.12: Soil moisture content in the rootzone using original and modified WAVE model versions (1990-1994)

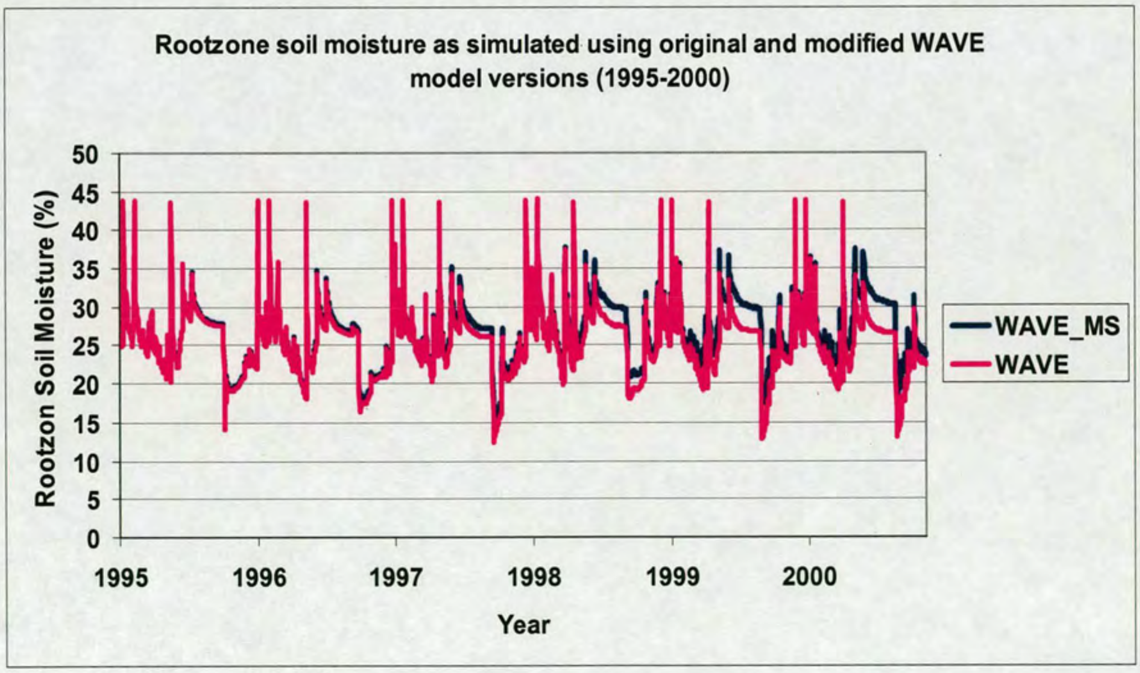


Figure 5.13: Soil moisture content in the rootzone using original and modified WAVE model versions (1995-2000)

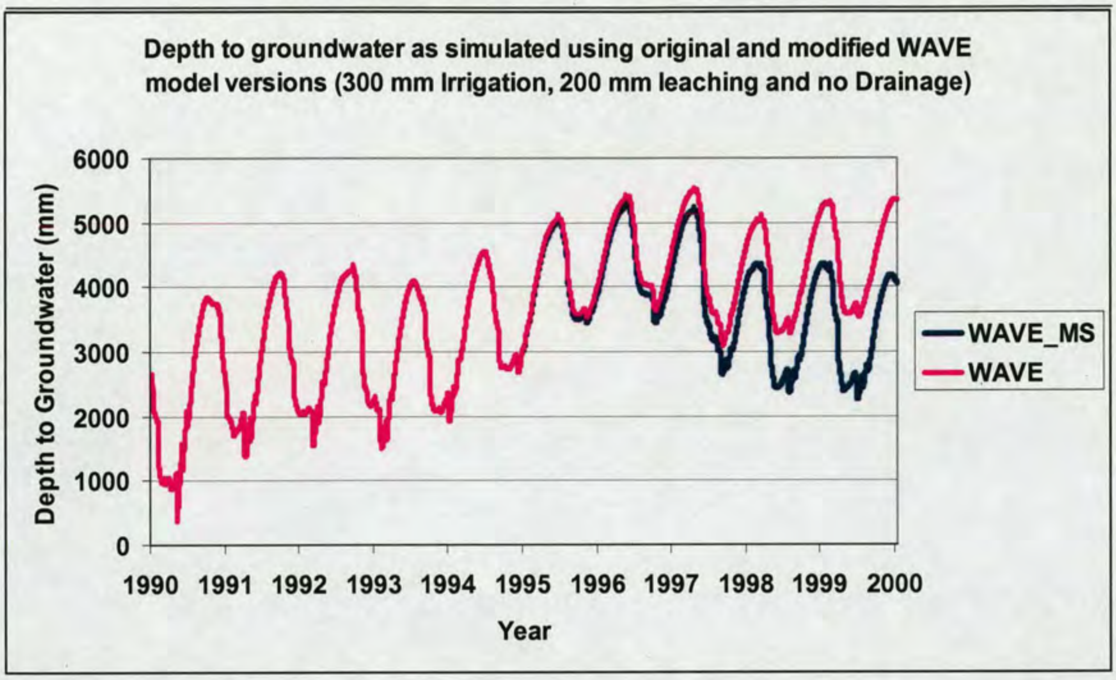


Figure 5.14: Groundwater depth using original and modified WAVE model versions (1995-2000)

These test results verify that the WAVE_MS model is capable of dealing with the combined effects of water and salinity stress. The results produced were satisfactory and as would have been expected. Full verification of the modified model would require experimental lysimeter data that were not available for this research. An impact of incorporating salinity stress is that water stress is reduced, as actual evapotranspiration is reduced through salinity stress.

As mentioned in section 5.4.1 above, the WAVE model calculates crop yield based on a yield reduction factor that represents a proportion of maximum yield. The final yield reduction factor is based on the product of three separate yield reduction factors, those due to waterlogging, water stress, and salinity stress. In the WAVE_MS model, the potential evapotranspiration is reduced to a lower level when soil salinity in the rootzone exceeds certain value. This is not considered in the WAVE model. A comparison of the crop yield response produced from WAVE_MS and from WAVE results is presented in Table 5.4. The relative influence of soil salinity on crop yield over 11 years simulation period using both WAVE and WAVE_MS shows that crop yield as simulated using both versions was exactly the same for the period 1990-1994 as soil salinity did not exceed the threshold value because crop evapotranspiration remains the same over this period. Crop yield simulated using WAVE_MS starts to decrease below that simulated using WAVE for the period 1995-2000 because the soil salinity exceeds the threshold value above which the evapotranspiration decreases below its potential value.

Table 5.4: Simulated cotton yield using original and revised WAVE model versions

Year	WAVE	WAVE_MS
1990	0.94	0.94
1991	0.91	0.91
1992	0.90	0.90
1993	0.91	0.91
1994	0.91	0.91
1995	0.84	0.82
1996	0.81	0.79
1997	0.80	0.73
1998	0.85	0.72
1999	0.80	0.71
2000	0.67	0.62

5.6 Conclusions

In this chapter the theory behind the WAVE model has been described. As part of this research, the model has been modified by incorporating the effect of salinity in addition to the effect of water stress on crop transpiration. The new version of the model is called WAVE_MS. The modifications have been successful. The crop transpiration calculated by the revised model was lower than that calculated using the original version once soil salinity exceeded the threshold value for salinity stress. The root zone soil moisture and the ground water level were higher with the revised model because of the decrease in the crop transpiration. Full verification against experimental results has not been possible, however.

Crop yield is also affected by the modifications in WAVE_MS. Crop yields simulated by WAVE_MS were lower than those simulated using the original version, once soil salinity exceeded the threshold value. The decrease in the crop transpiration due to salinity stress simulated using WAVE_MS resulted in further yield reduction.

CHAPTER 6

WAVE Model Set-up and Calibration

6.1 Introduction

The ability of any mathematical model to produce reliable output depends on the availability of reliable input data, as well as the accuracy of the model in representing the physical processes of the prototype. In most systems being modelled there are process representations that cannot be adequately parameterised by field measurement alone, perhaps because of high spatial variability. Because of this, most models require calibration. Calibration is the process through which model parameters are modified to enable the model to closely match the field observations (Gupta *et al.,* 1998). In the WAVE model, the parameters are those required by the van Genuchten equation (van Genuchten, 1980):- saturated and residual soil moisture content (θ_s and θ_r), the inverse of the air entry value (α), the shape parameters (n and m). For salinity modelling the solute distribution constant (K_d) requires calibration.

Field determination of these parameters is very difficult and values may vary widely between relatively close locations. These variations can be very wide and limit the direct use of measured properties (Smets *et al.,* 1997). Trial and error procedures can be used, however, to refine parameter values to those that yield optimum simulation of soil moisture and salinity. This is the calibration approach adopted here.

The WAVE_MS model has been calibrated using the field data collected under the WRMLIP project. This chapter describes the WAVE_MS model set-up and presents the calibration processes and results. It also provides an evaluation of the calibration results, an assessment of the model performance and of its potential in establishing efficient water and drainage management strategies.

Following this introduction, sections 6.2 and 6.3 describe the field data collected on soil, irrigation, agronomy and meteorology. Section 6.4 discusses the values of model parameters adopted for the WAVE_MS modelling in this research. Section 6.5 describes the WAVE_MS model calibration, provides an assessment of the calibrated model performance, and of its potential in establishing efficient water and drainage management strategies. Concluding remarks are presented in section 6.6.

6.2 Field Data

Mott MacDonald (2003a) have presented field data collected at three pilot areas in the Makhtaaral region of South Kazakhstan. The programme commenced in October 2000. The objective of the data collection programme was to collect the data necessary to calibrate the mathematical models of the irrigation system being developed by the WRMLIP project. In particular the data were required for the WAVE model, which was a part of the On Farm Water Distribution Model (OFWDM) (Mott MacDonald, 2000b).

The following data were collected during 2001 at each pilot area (Mott MacDonald, 2002):

- Daily meteorological data for the Lenina weather station, including rainfall, daily air temperature and relative humidity data. There were no sunshine or wind speed data reported in the 2001 data collection programme.
- Physical soil characteristics (size distribution, bulk density, porosity, infiltration, field capacity, wilting point etc.). Soil characteristics have been observed at a number of locations in each of the pilot areas, with sampling at different depths from the surface to a depth of 3 m.
- Time series of soil moisture characteristics with depth based on laboratory analysis of soil samples collected.
- Chemical composition of irrigation water, soils, groundwater and drainage water.
- Time series of groundwater levels.

- Leaching and irrigation water applications, timing and field distribution.
- Crop characteristics for cotton, including planting dates, development stages, rooting depths and yields.
- An evaluation of water and salt balances in the pilot areas during 2001.

The field data collection programme in 2001 provided infiltration characteristics at different depths as well as definition of permanent wilting point and saturated moisture content at different depths. These data were obtained by laboratory analysis of soil samples taken at 200 *mm* depth intervals from the three pilot areas, with 9 sampling locations in each pilot area. The WAVE_MS model was set-up for each location using the terminal infiltration rate and soil properties for the sampling point closest to that location as model input. There were no measurements of soil moisture tension data during the 2001 collection programme. The pilot areas were Birlik, Karaoi and Makhtali. The locations of the pilot areas are shown in Figure 6.1. Figures 6.2, 6.3 and 6.4 show the sampling locations in each of the pilot areas for the 2001 data collection programme.

In 2002, automatic soil monitoring equipment was installed in the pilot areas and fieldwork carried out between February and November. The monitoring programme with the automatic equipment allowed both continuous and discrete observations. The equipment installed and the parameters measured are summarised in Table 6.1.

Figures 6.5, 6.6 and 6.7 show the locations of equipment at the Birlik, Makhtali and Karaoi pilot areas for the 2002 programme. Soil moisture tension data was measured using permanent Watermark sensors and gypsum blocks. The permanent Watermark sensors were installed at the centre of each pilot area to provide measurements at depths of 300 mm and 1000 *mm*, at every site, and additional measurements at 2500 *mm* at Makhtali, 2000 *mm* at Birlik and 3000 *mm* at Karaoi. The gypsum Blocks were installed at Makhtali (location P9) and Karaoi (location P6) at depths of 300 *mm*, 600 *mm*, 1000 *mm*, and 1500 *mm* (Mott MacDonald, 2003b). However, no soil moisture tension data were available for Birlik sites P3 and P12. The observed soil moisture tension data collected from the central site of Birlik were used in the calibration of other sites in Birlik pilot area.

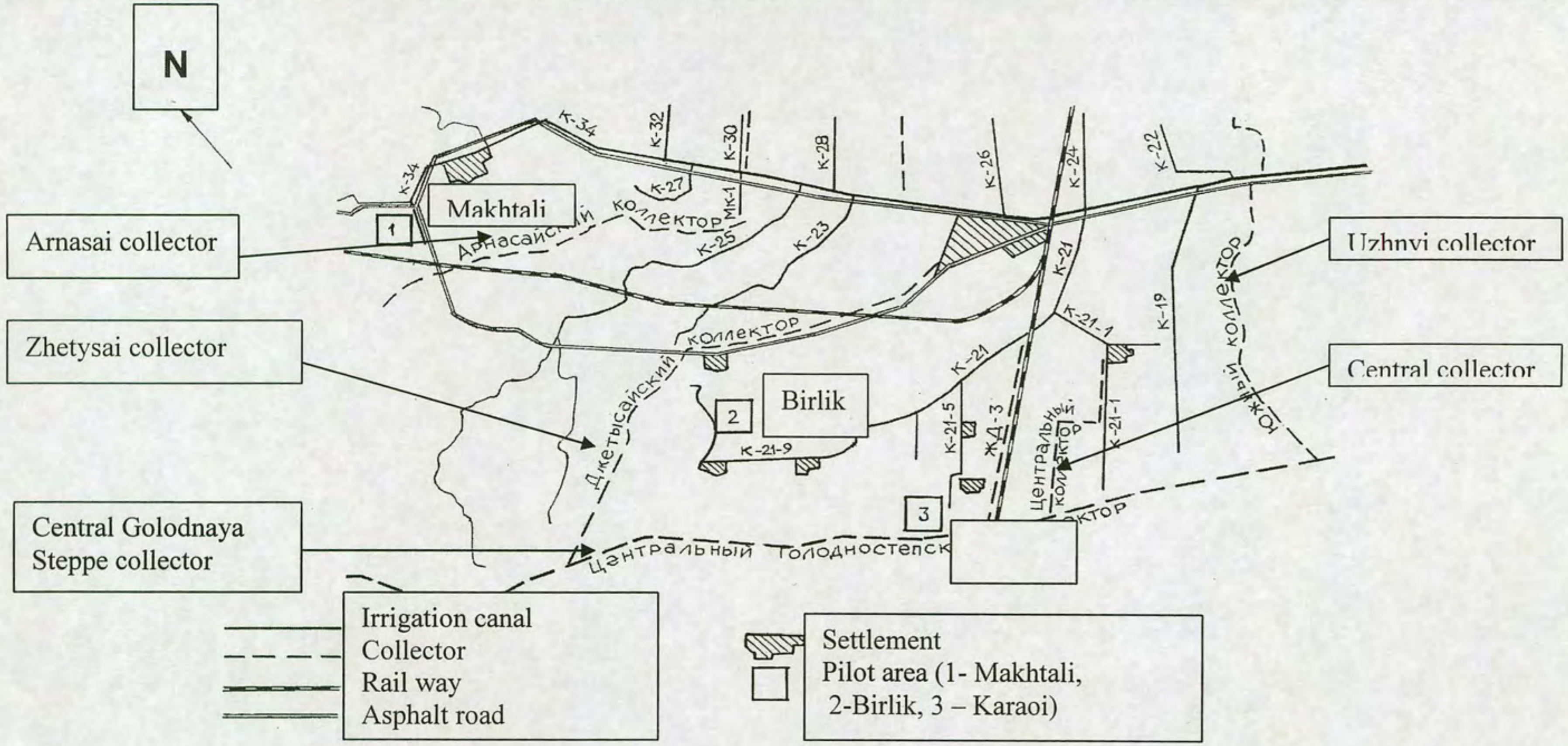
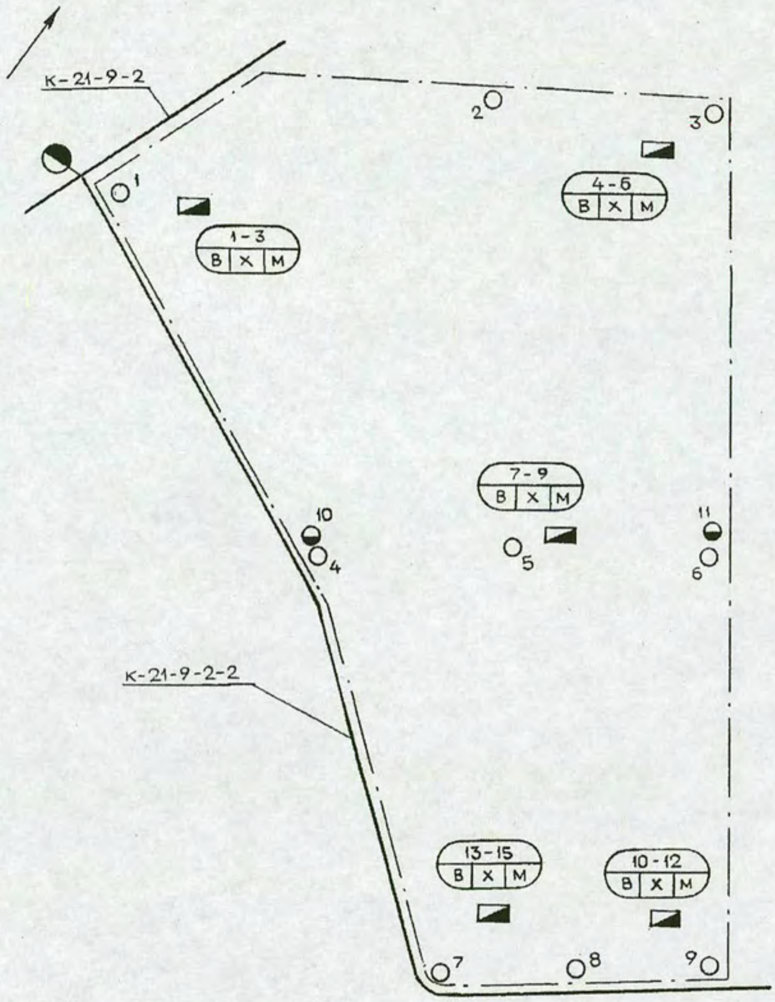


Figure 6.1: Pilot area locations (Mott MacDonald, 2003a)



- Irrigation canal
- Boundary of pilot area
- Soil property definition point:
B – water-physical; X – chemical; M - mechanical
- Vertical Drainage Well
- Observation well 7 m
- Deep observation well 35 m

Figure 6.2: Sampling locations at Birlik (Mott MacDonald, 2002)

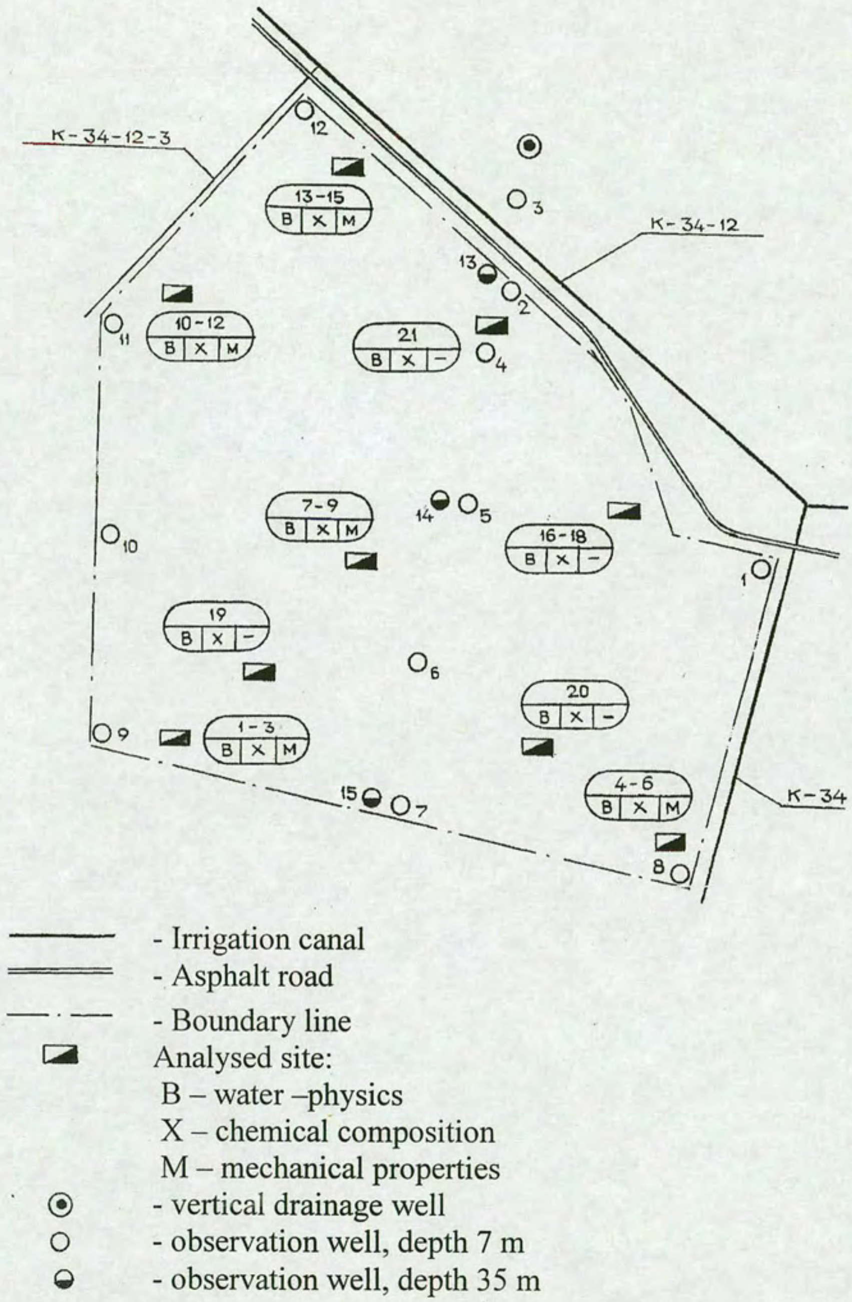


Figure 6.3 Sampling locations at Makhtali (Mott MacDonald, 2002)

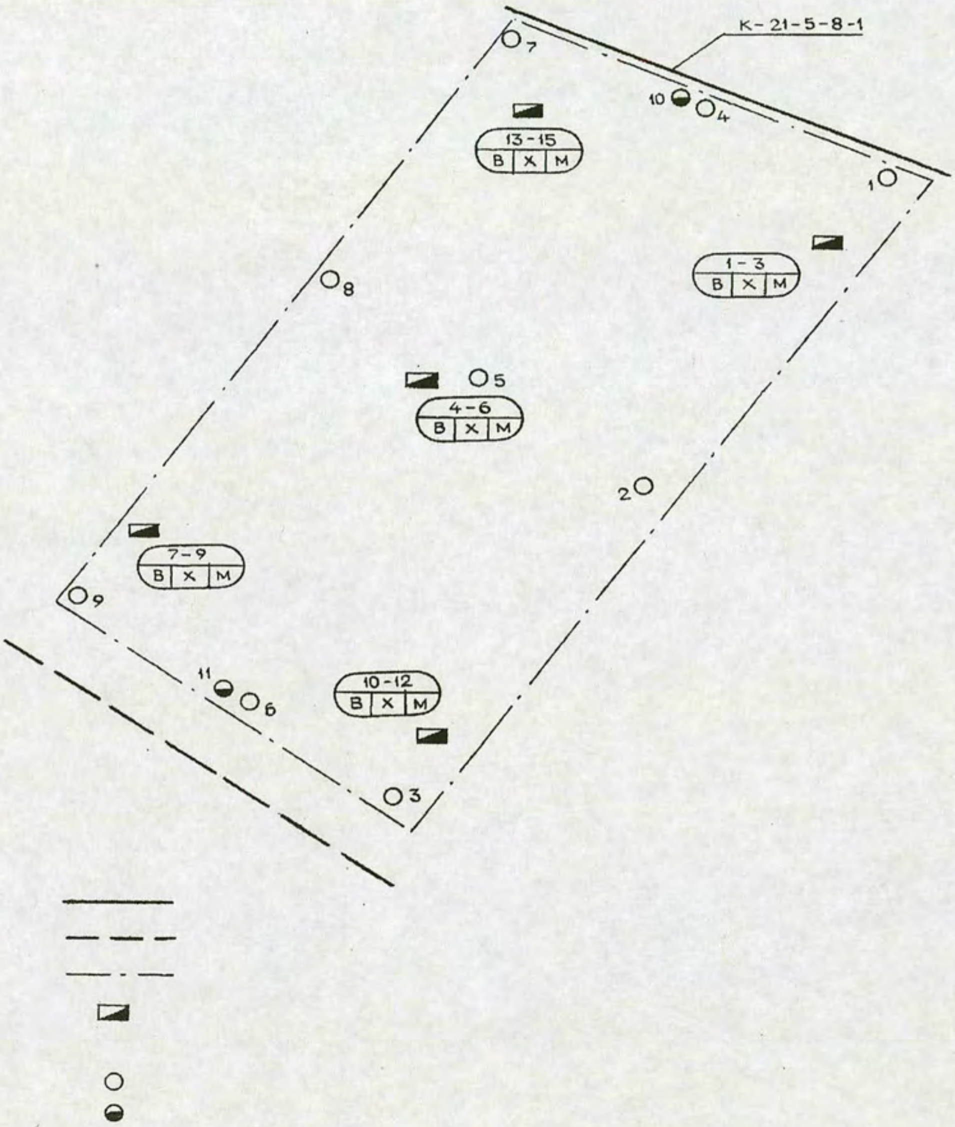


Figure 6.4: Sampling locations at Karaoi (Mott MacDonald, 2002)

Table 6.1: Soil monitoring equipment used

Name	Parameter measured	Measurement range
Equitensiometer EQ2	Soil moisture tension	-100 to -1000 kPa
Watermark sensor WMSM	Soil moisture tension	0 to -200 kPa
Gypsum block GYP1	Soil moisture tension	-50 to -1500 kPa
Diviner 2000	Soil moisture in a profile; portable meter can be used on a large number of sites	% moisture by volume
EnviroScan	Soil moisture at particular depths in a soil profile; equipment fixed and gives continuous readings	% moisture by volume
Sigma probe EC1	Soil salinity	0 to 1000 mS/m
Temperature meter TM1	Soil temperature	-20°C to +80°C

Source: Mott MacDonald (2003b)

Soil moisture was measured at a large number of sites in each pilot area using the Diviner probe, which is portable and permits a soil moisture profile to be observed. Soil moisture was also measured at three depths (300, 600 and 1000 *mm*) at the centre of each pilot area using the EnviroScan sensor. This equipment was fixed and permited continuous measurements. A considerable number of dual measurements of soil moisture by Diviner probe and gravimetric laboratory analysis were carried out in each pilot area. However, the evaluation of the soil monitoring equipment results highlighted certain problems associated with the data obtained from both the soil monitoring equipment and from gravimetric soil moisture analysis. Significant variations were found between the data measured by each of the methods.

The 2002 field data collection programme also provided soil electrical conductivity measurements using a Sigma Probe. A problem associated with this instrument was that, it was unable to produce reliable measurements of conductivity in the very dry soil samples for the top 200 *mm* of soil (Mott MacDonald, 2003b).

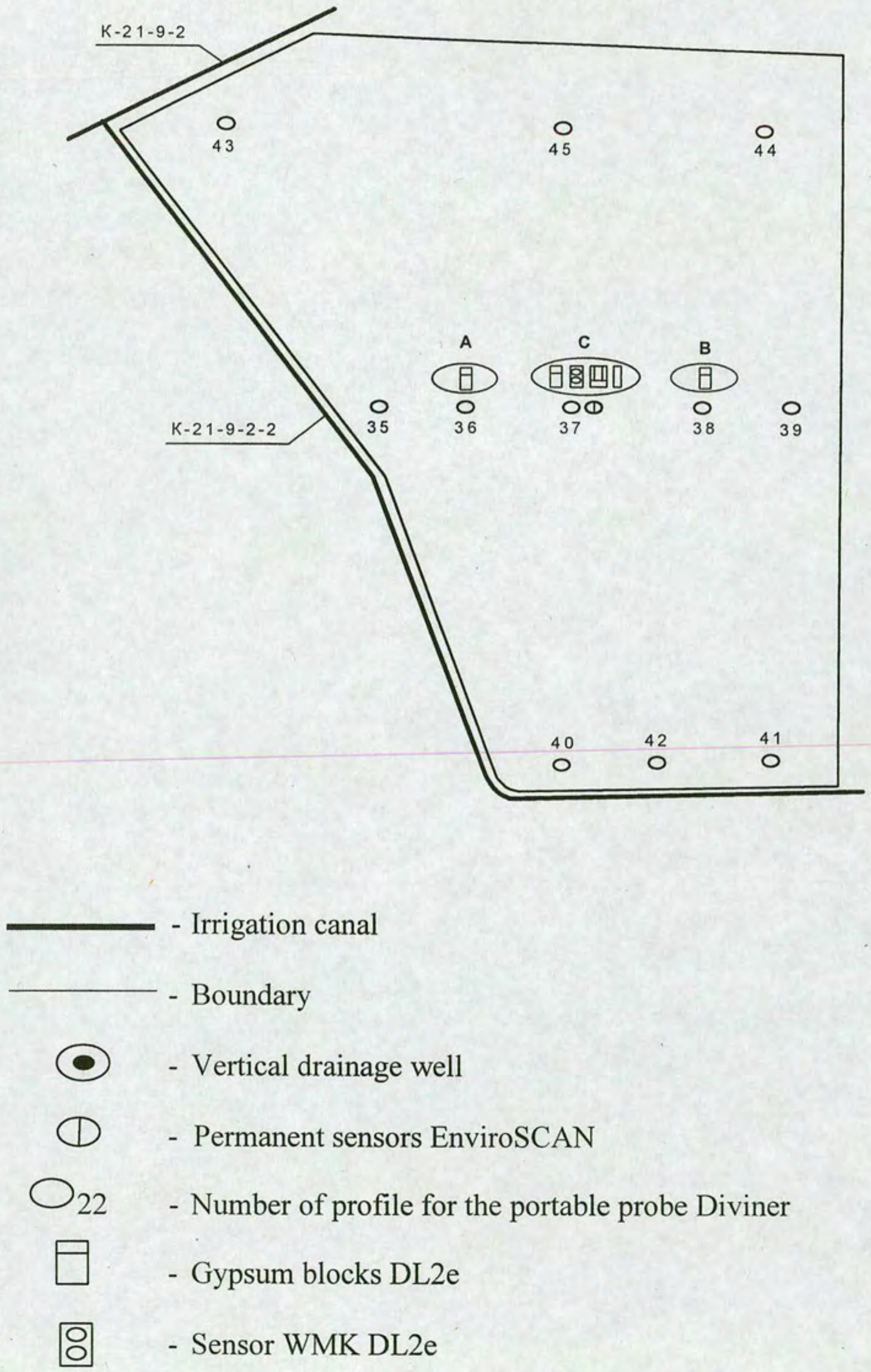
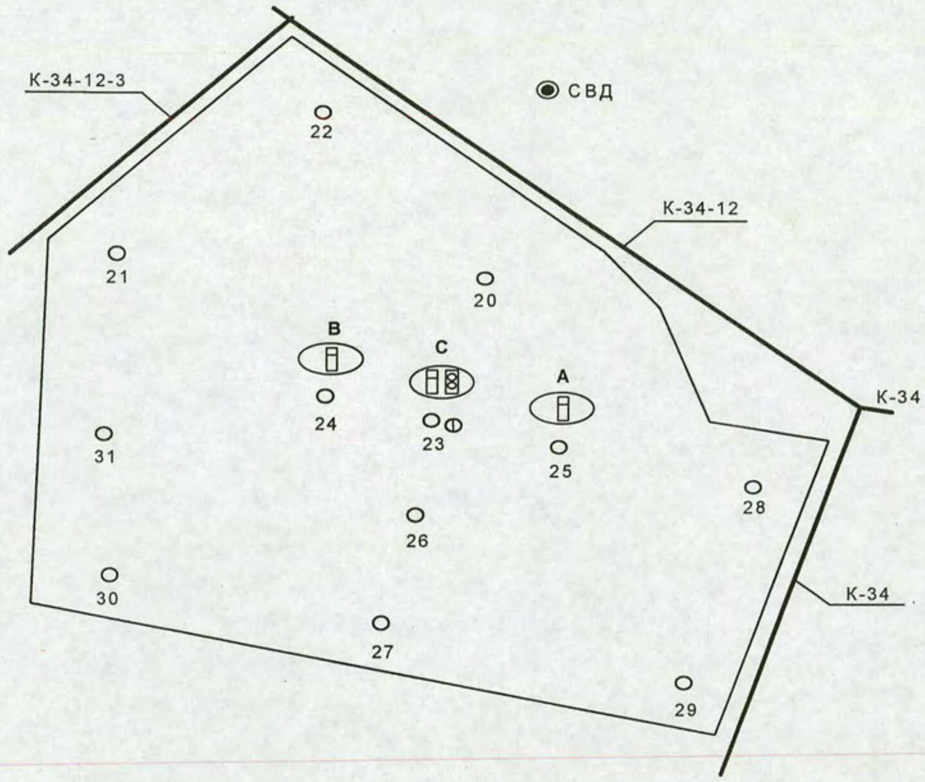


Figure 6.5: Location of equipment at Birlik (Mott MacDonald, 2003b)



- Irrigation canal

- Boundary

- Vertical drainage well

- Permanent sensors EnviroSCAN

22 - Number of profile for the portable probe Diviner

- Gypsum blocks DL2e

- Sensor WMK DL2e

Figure 6.6: Location of equipment at Makhtali (Mott MacDonald, 2003b)

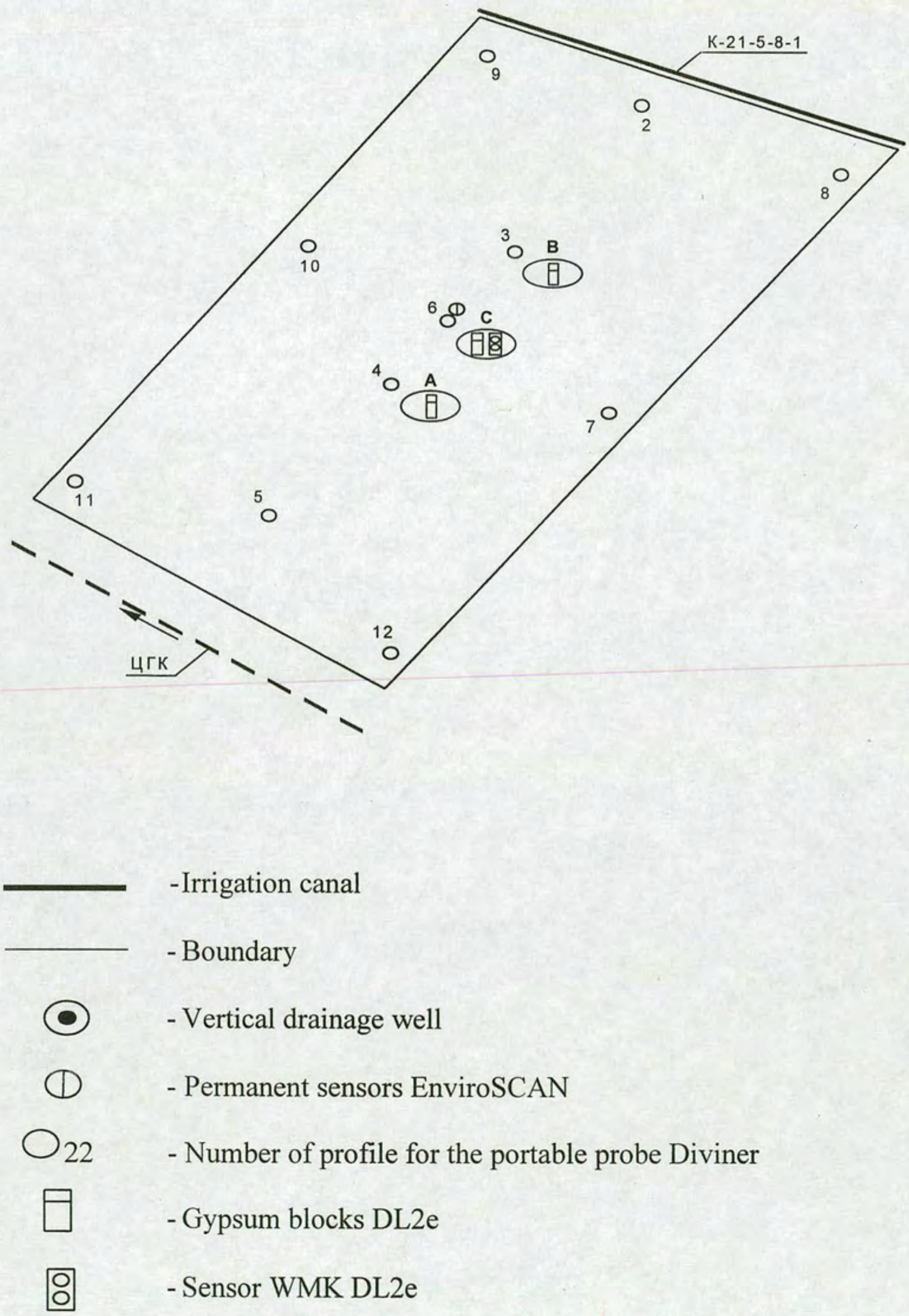


Figure 6.7 Location of equipment at Karaoi (Mott MacDonald, 2003b)

6.3 Data Available

6.3.1 Meteorological Data

The climate of South Kazakhstan is continental. The semi-arid steppes are characterised by extremely low rain, hot summers and cold winters. Climatic data were available from the Lenina weather station for the period 1990-2001. Lenina lies in the centre of the project area and is representative of the area (Mott MacDonald, 2000b). The WAVE model requires daily rainfall and reference crop evapotranspiration data as primary input.

The coldest month is January in which the mean daily air temperature is about $-2.0\,°C$. The hottest month is July with an average of $27.9\,°C$. Mean monthly air temperatures are indicated in Figure 6.8. The climatic conditions limit the growing season to between April and October, although rainfall in this period is insufficient to meet the water requirements of most crops. The annual rainfall averages 310 mm and this falls mainly in winter and spring. Figure 6.9 shows mean monthly rainfalls. The average monthly wind speed ranges from 1.2 m/s (103 Km/day) to 2.0 m/s (172 km/day) and the area classified as a zone of light winds (less than 175 Km/day, WUFMAS, 1999). Figure 6.10 indicates that the windiest period generally is from January to May with wind speed around 2.0 m/s (172 Km/day). The highest relative humidity is recorded in January, February and December at 83%, 80% and 80% respectively. Lowest values of relative humidity of 45% and 46% occur in June and July respectively. Mean monthly relative humidity is shown in Figure 6.11.

Mean monthly reference crop evapotranspiration, ET_o, was determined for Lenina by Mott MacDonald (2000b) and is shown in Figure 6.12. Potential evapotranspiration reaches its highest value of 6.9 mm/day in June. The lowest average evapotranspiration values of 0.67 mm/day and 0.65 mm/day occur in January and December respectively.

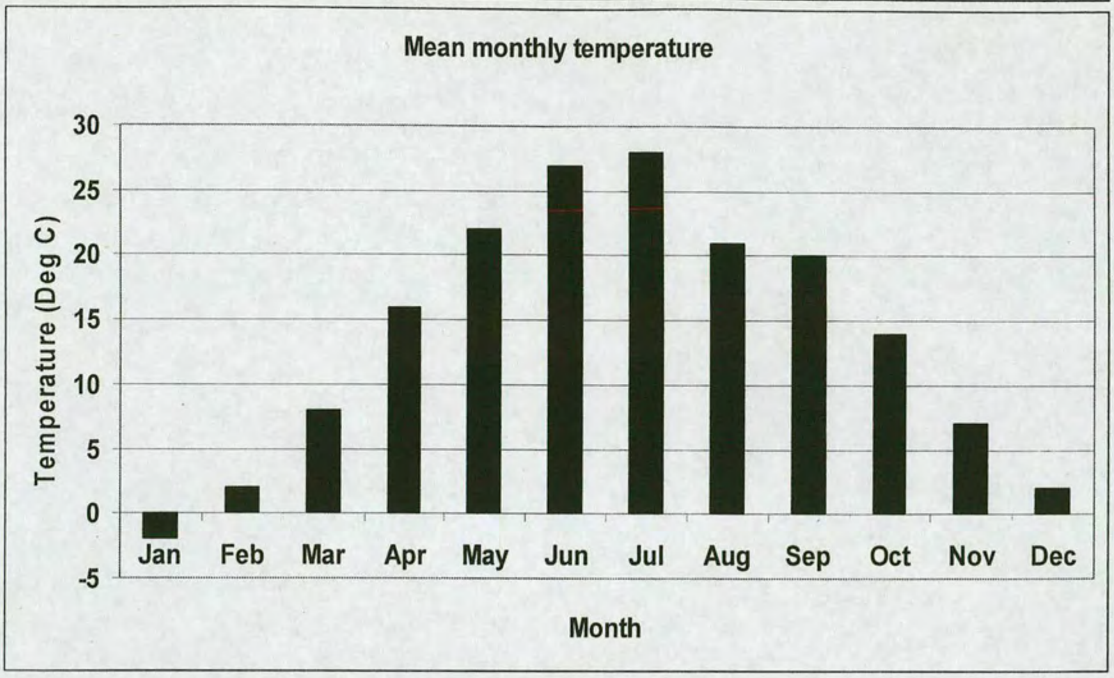


Figure 6.8: Mean monthly air temperature

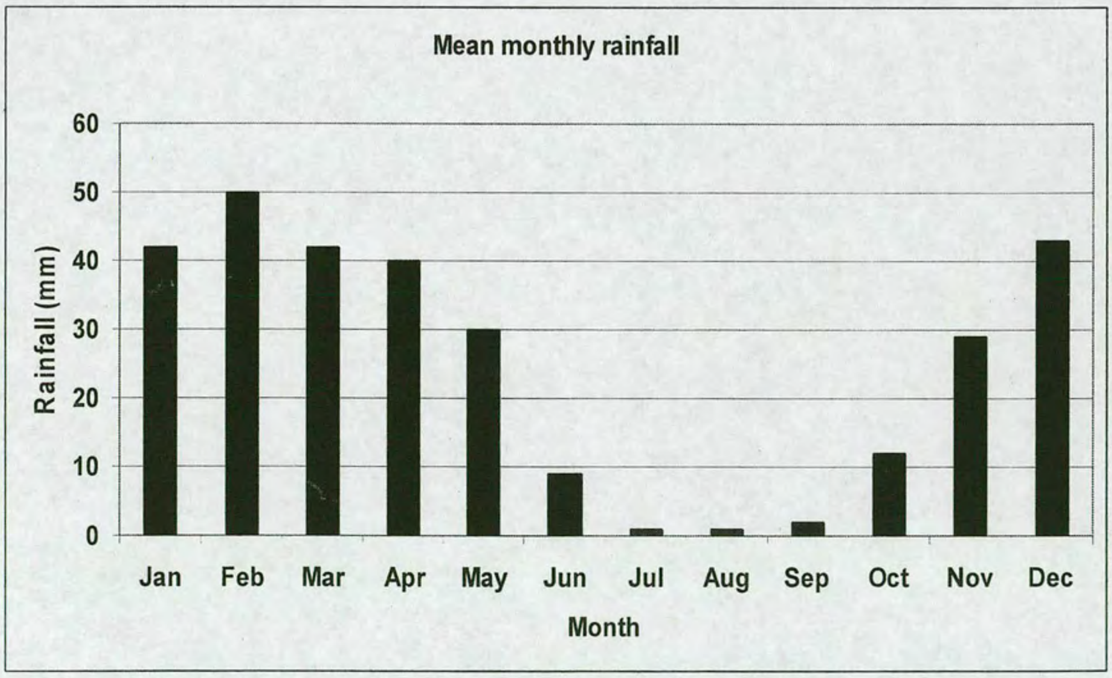


Figure 6.9: Mean monthly rainfall

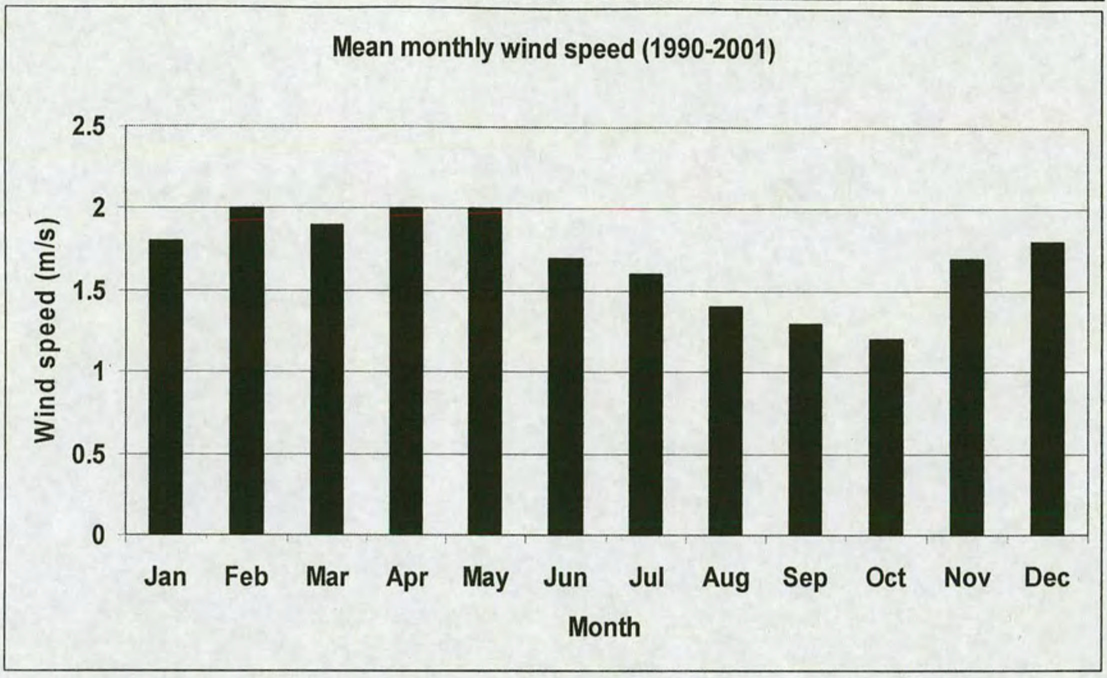


Figure 6.10: Mean monthly wind speed

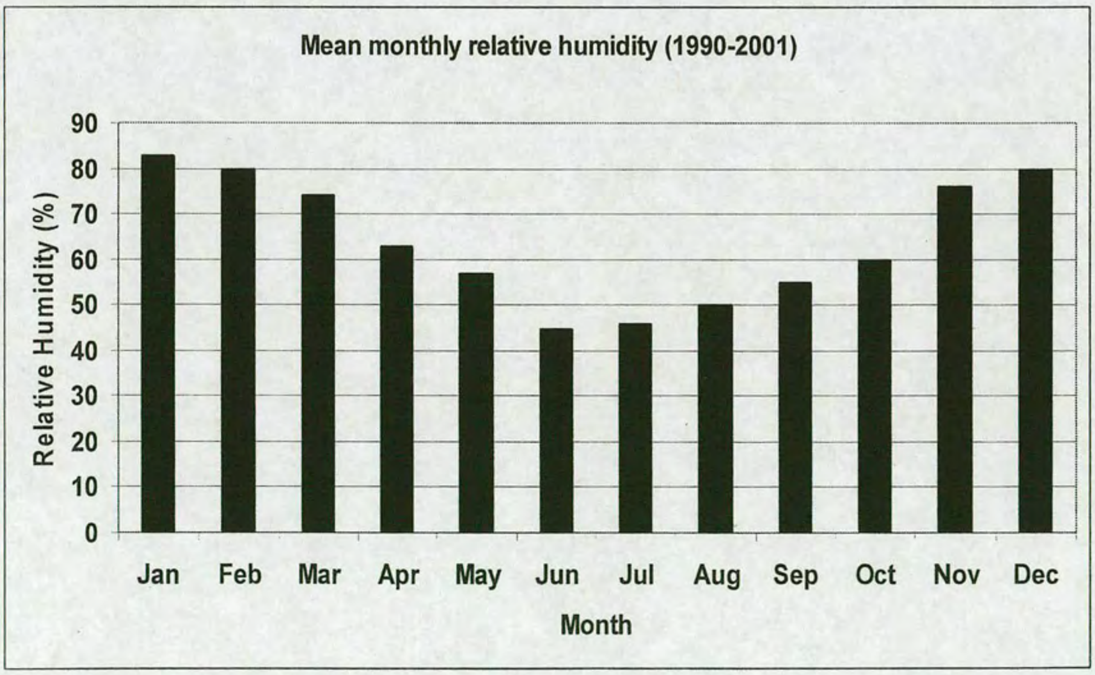


Figure 6.11: Mean monthly relative humidity

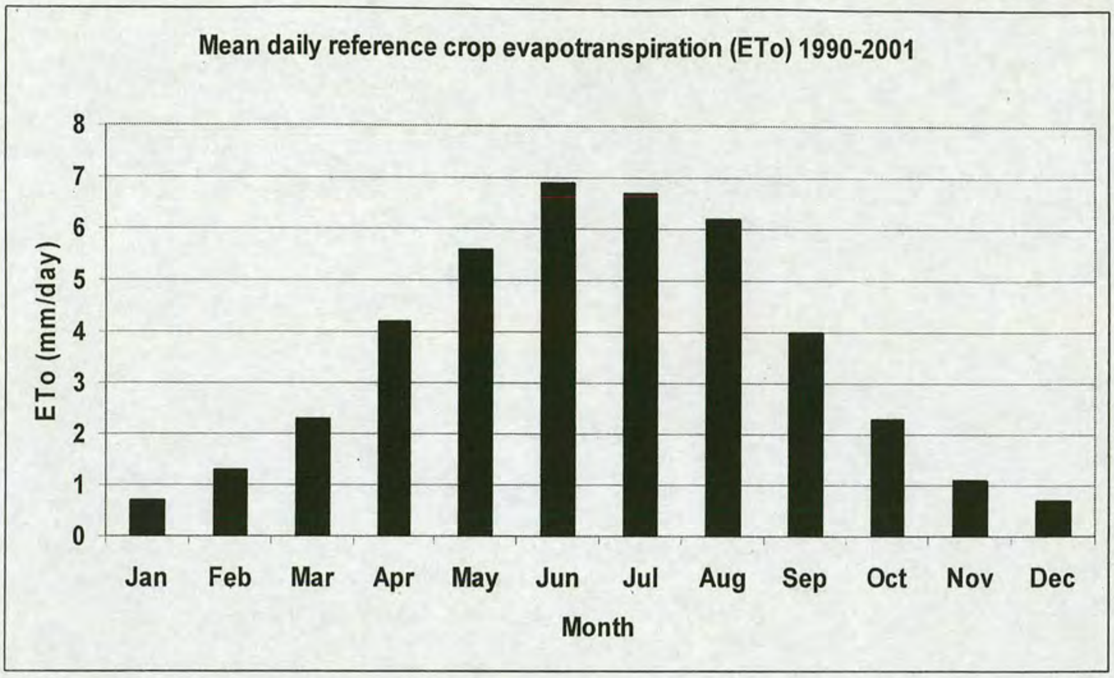


Figure 6.12: Mean daily reference crop evapotranspiration

6.3.2 Soil characteristics

The WRMLIP field data collection programme provided both soil physical and chemical property data. These included porosity, soil texture, bulk density, saturated permeability, field capacity, permanent wilting point, and soil salinity.

Table 6.2 presents average soil physical properties for the three pilot areas. The organic matter content in the project area was very low at 1.0%-1.5%. According to the Kachinsky classification criteria (WUFMAS, 1999), the upper soil layers, mostly to 1-meter depth are classified as medium loam whereas light loam is the most common classification in the lower 2 meters of the soil profile. The average values of bulk density over all the soil layers are in the range from 1.42-1.67 g/cm^3, 1.41-1.7 g/cm^3 and 1.41-1.56 g/cm^3 in the Makhtali, Birlik and Karaoi pilot areas respectively. Higher bulk density values were identified in the ploughpan layer 20-40 cm. The average porosity values ranged from 36.5%-46.2%, 37.5%-47.2% and 43.0%-47.2% in the Makhtali, Birlik and Karaoi pilot areas respectively. No significant variations in the soil porosity were identified between the three pilot areas. Soil is classified as dense (compact) when the total porosity is below 10%, moderately porous when it ranges between 10% and 25%, porous when it ranges between 25% and 40% and extremely porous when its porosity over 40% (Pagliai *et al.,* 2003). Accordingly, the soil of the study area can be considered as extremely porous in most depths. According to the field capacity and wilting point values presented, the average available water content (AWC) were 66, 62, and 53 *mm* of water per metre of soil profile for Makhtali, Birlik and Karaoi respectively.

The WRMLIP data collection report provided soil salinity data at different depths for each pilot area in terms of total soluble salts (TSS) along with the ionic balances in % of salts by weight of dry soil. Local classification of salinity is based on the percentage of salts by weight in an aqueous extract of soil and on chloride concentration, whereas the International classification of salinity is based on the electrical conductivity (EC) of a saturation extract of the soil (WUFMAS, 1999). There were no electrical conductivity measurements available in the years 2000 and 2001. However, a relationship was established between percentages of total soluble salts (TSS) and electrical conductivity (EC) (Mott MacDonald, 2003b) on the basis of EC measurements in 2003. This relationship was presented in Chapter 5.

Table 6.3 presents average chemical properties of the soils in the pilot areas at the start of the data collection programme, based on 2000 and 2001 data. The average values of TSS for each layer were used as initial values for WAVE_MS. According to the local classification, soils in Makhtali and Birlik is classified as highly saline in the upper soil layers to moderately saline in the bottom layers below the rootzone. Soils are classified as non-saline in the Karaoi area. On the basis of the international classification system (WUFMAS, 1999), the majority of layers in Makhtali and Birlik tend to be classified as highly saline, and in Karaoi are classified as slightly saline instead of non-saline with the local classification. Soil salinity in Makhtali and Birlik is above the threshold value for damage to most crops based on the criteria described in the FAO Irrigation and Drainage Paper 56 (Allen *et al,* 1998). However, it is still below the threshold value in Karaoi.

Soil salinity has significantly increased in the WRMLIP project area since 1990 (Figures 6.13 and 6.14). There has been a significant increase in the area classified as moderately saline. The total area classified, as moderately saline in 1990 was 4495 hectare (21% of the Phase I area) and 6123 hectare (29% of the Phase II area) in the Phase I and Phase II areas respectively. Within a 9 year period, these areas had increased to be 9644 hectare (45% of the Phase I area) and 10334 hectare (49% of the Phase II area) in the same phases respectively (Mott MacDonald, 2004). The average rate of increase has been 2.4% and 2.0% per year respectively.

6.3.3 Crop Characteristics

As mentioned earlier in Chapter 5, the WAVE model requires a number of crop characteristics, including crop coefficients (K_C), rooting depths and leaf area index (LAI) at various stages of growth. Data on cotton stages of growth were collected during the 2001 field data collection programme. The length of cotton growth stages and the values of K_C used during the modelling are presented in Table 6.4.

The data collection report (Mott MacDonald, 2003a) also provides root depth and distribution data in each of the pilot areas, measured during 2001. These data were used as input in the WAVE_MS model. These data are presented in Table 6.5.

Leaf area indices are used in the WAVE model to partition evapotranspiration into evaporation and transpiration. These data were not collected during 2001 for the pilot areas. The leaf areas used in modelling are presented in Table 6.6.

Table 6.2: Average values of some soil physical characteristics in study locations

Pilot Area	Layer (cm)	Soil Class	$Bd\ g/cm^3$	θ_{FC} $(\%)$	θ_{WP} $(\%)$	Porosity $(\%)$
Makhtali	0-20	Medium loam	1.42	21.1	12.7	46.2
	20-40	Medium loam	1.67	17.4	12.7	36.5
	40-60	Medium loam	1.54	18.0	13.0	41.3
	60-80	Medium loam	1.48	19.2	12.7	42.9
	80-100	Medium loam	1.47	20.2	13.3	44.4
	100-150	Light loam	1.48	20.4	-	44.6
	150-200	Light loam	1.49	20.3	-	44.8
	200-250	Light loam	1.48	-	-	45.0
	250-300	Light loam	1.49	-	-	44.1
Birlik	0-20	Heavy loam	1.45	18.7	13.7	47.2
	20-40	Medium loam	1.70	17.5	13.8	37.5
	40-60	Medium loam	1.50	18.1	13.8	45.0
	60-80	Medium loam	1.42	19.5	14.0	46.7
	80-100	Medium loam	1.41	20.8	13.9	46.8
	100-150	Medium loam	1.41	22.3	-	46.6
	150-200	Light loam	1.47	23.0	-	45.0
	200-250	Light loam	1.50	-	-	43.6
	250-300	Light loam	1.50	-	-	43.3
Karaoi	0-20	Medium loam	1.41	18.4	13.4	46.5
	20-40	Medium loam	1.56	17.8	13.5	43.0
	40-60	Medium loam	1.47	17.8	13.1	44.6
	60-80	Medium loam	1.42	18.1	12.6	47.2
	80-100	Light loam	1.43	18.9	12.4	47.2
	100-150	Light loam	1.43	18.5	-	46.8
	150-200	Light loam	1.43	18.6	-	45.5
	200-250	Light loam	1.46	-	-	44.7
	250-300	Light loam	1.45	-	-	44.9

Table 6.3: Average values of some soil chemical characteristics in study locations

Pilot Area	Layer (cm)	TSS (%)	Anion			Cation		
			HCO_3^-	Cl^-	SO_4^{2-}	Ca^{++}	Mg^{++}	Na^+
Makhtali	0-20	0.84	0.022	0.149	0.422	0.069	0.054	0.126
	20-40	0.95	0.019	0.131	0.519	0.089	0.058	0.130
	40-60	0.90	0.017	0.127	0.500	0.056	0.069	0.133
	60-80	0.69	0.018	0.102	0.373	0.053	0.052	0.094
	80-100	0.57	0.020	0.075	0.314	0.028	0.045	0.089
	100-150	0.38	0.018	0.018	0.240	0.054	0.022	0.029
	150-200	0.39	0.019	0.027	0.235	0.033	0.032	0.039
	200-250	0.40	0.017	0.026	0.245	0.062	0.018	0.034
	250-300	0.52	0.018	0.023	0.336	0.062	0.039	0.037
Birlik	0-20	0.86	0.021	0.096	0.501	0.050	0.068	0.124
	20-40	0.85	0.018	0.071	0.520	0.300	0.048	0.100
	40-60	0.62	0.019	0.073	0.348	0.032	0.047	0.097
	60-80	0.55	0.018	0.080	0.292	0.036	0.034	0.091
	80-100	0.51	0.018	0.074	0.268	0.023	0.036	0.088
	100-150	0.49	0.020	0.049	0.277	0.053	0.029	0.057
	150-200	0.47	0.017	0.047	0.281	0.029	0.044	0.055
	200-250	0.46	0.017	0.041	0.273	0.062	0.025	0.046
	250-300	0.49	0.017	0.032	0.309	0.035	0.046	0.047
Karaoi	0-20	0.08	0.027	0.008	0.026	0.008	0.006	0.007
	20-40	0.13	0.026	0.008	0.063	0.020	0.007	0.008
	40-60	0.19	0.022	0.008	0.105	0.030	0.010	0.010
	60-80	0.16	0.023	0.009	0.083	0.023	0.010	0.008
	80-100	0.15	0.022	0.009	0.077	0.019	0.011	0.009
	100-150	0.14	0.023	0.010	0.066	0.017	0.009	0.011
	150-200	0.11	0.022	0.008	0.047	0.009	0.008	0.019
	200-250	0.19	0.023	0.012	0.095	0.026	0.011	0.010
	250-300	0.32	0.026	0.014	0.150	0.103	0.011	0.011

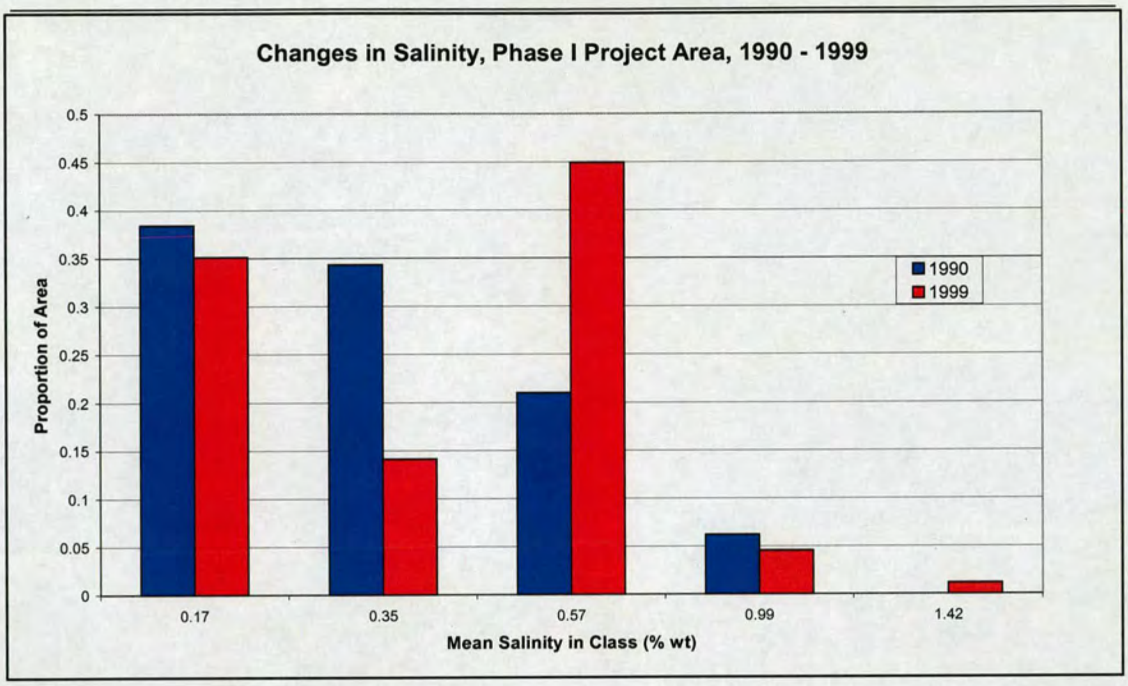


Figure 6.13: Changes in Salinity, Phase I Project Area (Mott MacDonald, 2004)

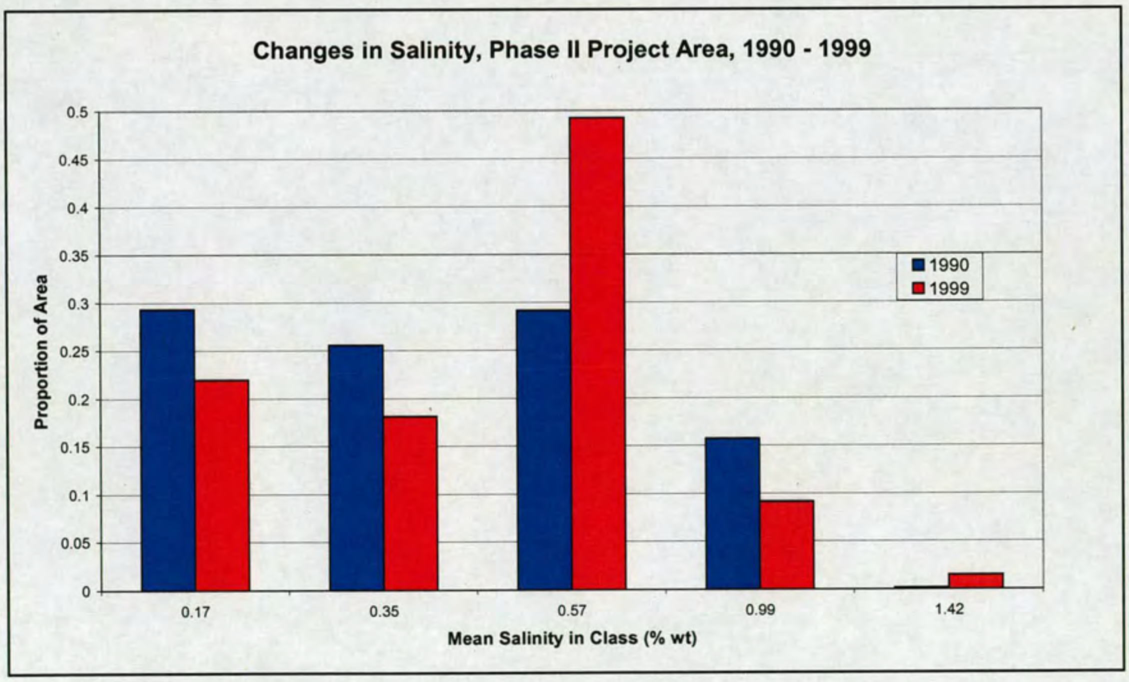


Figure 6.14: Changes in Salinity, Phase II Project Area (Mott MacDonald, 2004)

Table 6.4: Growth stages for cotton in pilot Areas

Stage of growth	Kc	Dates of Stage (and length in days)		
		Makhtali	Birlik	Karaoi
Planting	0.4	17/4	1/5	14/4
End Initial stage	0.4	19/5 (32)	31/5 (30)	18/5
End development	1.15	29/6 (41)	10/7 (37)	27/6 (40)
End mid stage	1.15	19/08 (52)	1/09 (52)	17/08 (50)
End late stage	0.6	15/10 (56)	15/10 (45)	15/10 (58)

Source: Mott MacDonald, (2002)

Table 6.5: Crop root development in each pilot Area

Makhtali		Birlik		Karaoi	
Date	Depth (mm)	Date	Depth (mm)	Date	Depth (mm)
29/5	400	9/6	200	27/5	600
29/6	600	10/7	600	27/6	1400
21/7	1400	3/8	1000	15/7	2200
14/8	2000	27/8	1600	12/8	2800
15/10	2400	15/10	1800	15/10	3000

Source: Mott MacDonald, (2002)

Table 6.6: Leaf area indices used in WAVE Modelling

Days from planting	Leaf area
6	0
7	2.35
37	5.60
150	6.40
181	0.0

Source: Mott MacDonald, (2002)

The yield response to water and salinity functions in the C_YIELD programme require the following data in addition to the data collected and used in the WAVE_MS model:

- Crop yield response factors required by Rao function (Rao *et al.,* 1988) to model crop yield response to water. In this research the C_YIELD model was set-up using crop yield response factors for each stage of growth published in Doorenbos and Kassam (1979). The values used for cotton were 0.20, 0.5, 0.45 and 0.25 for vegetative, flowering, yield formation and ripening growth stages respectively.
- Soil salinity threshold value, which is required to model yield response to salinity. For cotton, the value of the threshold salinity adopted was 7.7 dS/m, (Allen *et al.,* 1998).
- The rate, at which relative crop yield declines with increasing salinity, which is also required for salinity modelling. The model was set-up with value of 5.2 (Allen *et al.,* 1998).

6.3.4 Recent Irrigation Practices

Leaching water depths, dates of application and salinities in 2001 are presented in Table 6.7. Tables 6.8 and 6.9 show depths, dates and salinities of the irrigation water application. In 2001, irrigation water was applied only twice during the growth period between mid April and October. However, water was applied only once at Makhtali location P15, and at Birlik P3 and P12. Water application in Makhtali and Birlik was not uniform in either leaching or irrigation and varied across the pilot areas.

Table 6.7: Leaching applications at modelled locations within the project area, 2001

Location	Dates	Leaching Depth (mm)	Water Salinity (g/l)
Makhtali, location P3	11 Mar – 13 Mar	60	0.8
Makhtali, location P9	11 Mar – 13 Mar	60	0.8
Makhtali, location P15	6 Mar – 7 Mar	147	0.8
Birlik, location P3	26b Jan – 2 Feb	184	0.8
Birlik, location P12	8 Mar – 11 Mar	251	0.8
Karaoi, location P3	9 Mar – 15 Mar	156	0.792
Karaoi, location P6	9 Mar – 15 Mar	156	0.792

Table 6.8: First Irrigation applications at modelled locations within the project area, 2001

Location	Dates	Irrigation Depth (mm)	Water Salinity (g/l)
Makhtali, location P3	4 Jul – 5 Jul	65	1.436
Makhtali, location P9	4 Jul – 5 Jul	65	1.436
Makhtali, location P15	24 Jun – 25 Jun	86	1.436
Birlik, location P3	1 Aug – 2 Aug	33	1.2
Birlik, location P12	2 Aug – 3 Aug	65	1.2
Karaoi, location P3	28 May – 5 Jun	92	1.046
Karaoi, location P6	28 May – 5 Jun	92	1.046

Table 6.9: Second Irrigation applications at modelled locations within the project area, 2001

Location	Dates	Irrigation Depth (mm)	Water Salinity (g/l)
Makhtali, location P3	18 Aug – 20 Aug	70	1.214
Makhtali, location P9	8 Aug – 20 Aug	70	1.214
Makhtali, location P15	-	-	-
Birlik, location P3	-	-	-
Birlik, location P12	-	-	-
Karaoi, location P3	15 Jul – 18 Jul	43	1.128
Karaoi, location P6	15 Jul – 18 Jul	43	1.128

6.4 WAVE Model Parameterisation

This section discusses the values of model parameters adopted for the WAVE_MS modelling in this research.

6.4.1 Water Transport Parameters

As outlined in Chapter 5, the water transport module requires soil moisture retention and hydraulic conductivity parameters to be specified for each soil layer. These parameters are required by the van Genuchten (1980) equation. The WAVE model was set-up initially with soil hydraulic parameters derived from the field observations of soil moisture content and soil moisture tension. From the observed data, soil moisture content and soil moisture tension relationships were developed at each of pilot areas. As an example, Figures 6.15 presents a typical fitted soil moisture retention curves for Karaoi. The fitted soil moisture retention parameters were used as initial values in the calibration of soil moisture content and were expected to require further adjustments. Fitting of the soil moisture retention curves is presented in section 6.5.3.

Table 6.10 presents the critical pressure head values used to model the effect of water stress on crop transpiration according to the function proposed by Feddes *et al.*, (1978). These values were based on the values recommended in the WAVE reference manual (Vanclooster *et al.,* 1994).

Crop coefficients and leaf area indices values used for the WAVE_MS modelling are presented in Table 6.6.

The top boundary condition is determined by the allowable minimum pressure head at the soil surface and the maximum ponding depth. A maximum ponding depth of 10 *mm* has been used. When the maximum is reached, the excess water runs off. The lower boundary condition was specified by the observed groundwater level, for calibration purposes.

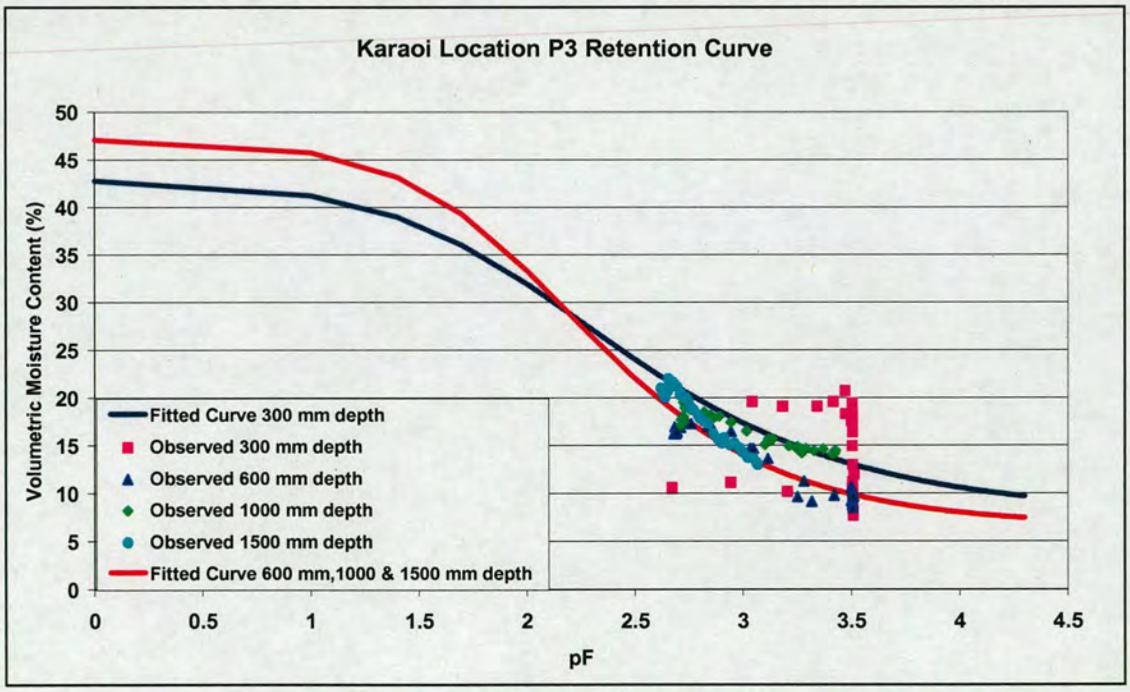


Figure 6.15: Fitted soil moisture retention curves, Karaoi area.

Table 6.10: Critical pressure head values used in WAVE modelling

Parameter	Description	Value
h_0	The pressure head below which the plant roots start to extract water from the soil	-10
h_1	The pressure head below which the roots start to extract water optimally from the soil	-46
h_2	The pressure head below which the roots can no longer extract water optimally	-500
h_2	The pressure dead at which the water uptake by plant roots ceases	-16000

6.4.2 Solute Transport Parameters

There are several parameters that need to be specified for use in the solute transport module. Table 6.11 lists the model parameters used along with the values adopted.

Table 6.11: Solute transport parameters used in WAVE modelling

Parameter	Description	Value
Dif	Chemical diffusion coefficient of the considered solute in pure water ($mm^2\ day^{-1}$)	0.01
a_k	Empirical constant used in the calculation of the effective diffusion coefficient	0.075
b_k	Empirical constant used in the calculation of the effective diffusion coefficient	10
f	Fraction of the adsorption sites situated in contact with the region	1
K_d	Distribution coefficient ($Litres\ Kg^{-1}$)	5
λ	The soil solute dispersivity (mm)	77
α	Empirical transfer coefficient (day^{-1})	0.01

The a_k, b_k and f values are based on the values recommended in the WAVE reference manual (Vanclooster *et al.,* 1994). Most other values are based on field data. f, and α are required when the mobile/immobile concept is considered.

6.5 WAVE_MS Model Calibration

6.5.1 General

Mott MacDonlad reported on preliminary WAVE model calibration on the 2001 field data (Mott MacDonald, 2002). Although this was restricted by the lack of soil tension data, they considered that the calibration results obtained were very encouraging. More refined calibration was carried out when the 2002 field data became available (Mott MacDonald, 2003c). The calibration carried out by Mott MacDonald was using the original form of the WAVE model. This section presents calibration of the WAVE_MS model.

The WAVE_MS model was set-up and calibrated using the field data from October 2000 to October 2002. Calibration was based on simulation of soil moisture content, and soil moisture tension (which was available for 2002 only), and soil salinity. Figure 6.16 provides an overview of the WAVE_MS model set-up and calibration.

6.5.2 Methods of Establishing Simulation Quality

To assess the simulation quality and subsequently the calibrated model performance, some statistical tests (Loague and Green, 1991; Vazquez and Feyen, 2003; Xevi *et al.,* 1996; Legates and McCabe, 1999) were used. A complete evaluation of model performance should include at least one "goodness-of-fit" or relative error measure and at least one absolute error measure with additional comparison parameters such as simulated and observed mean and standard deviation (Legates and McCabe, 1999). The statistical measures used in evaluating simulation quality, are mentioned below.

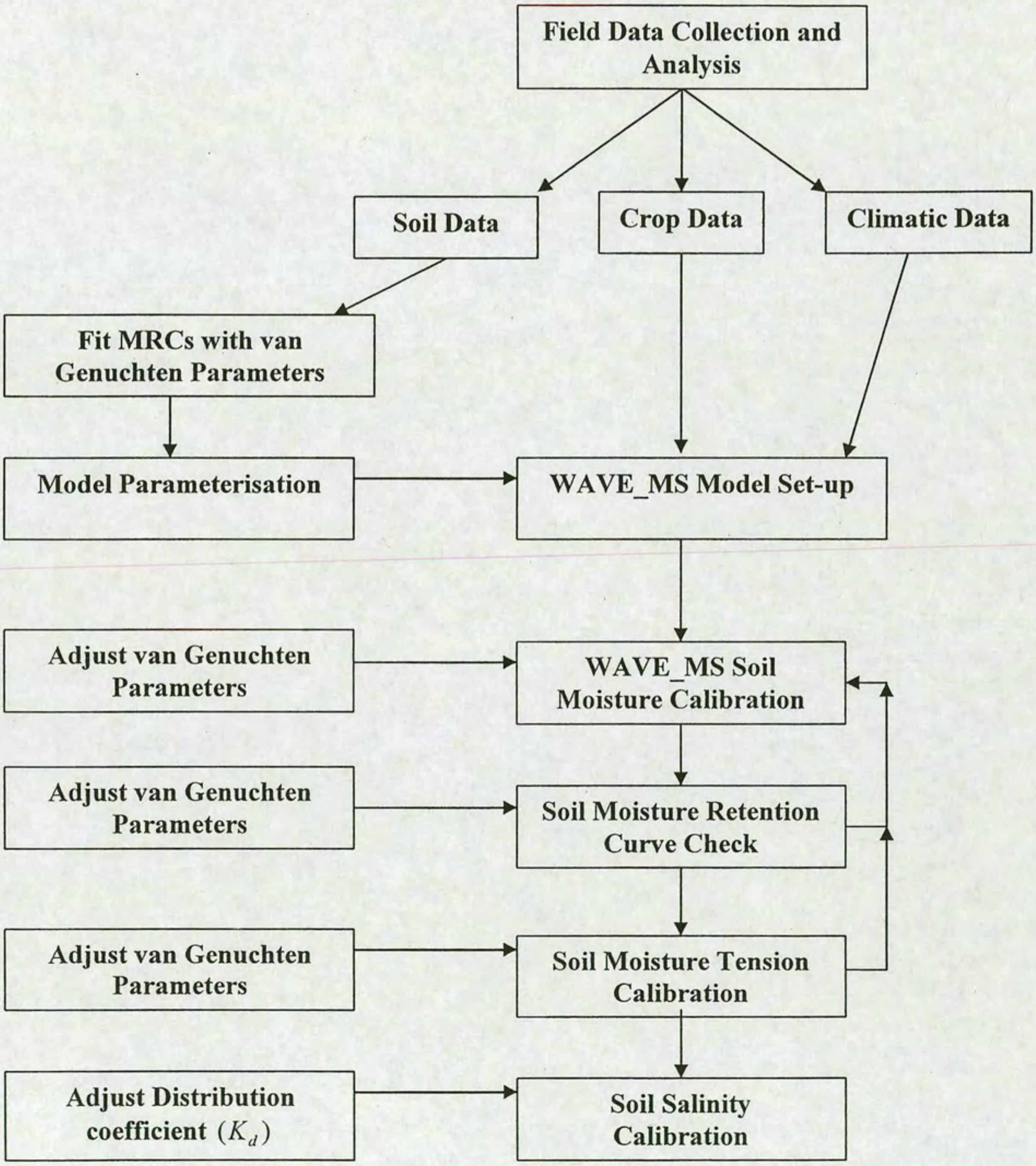


Figure 6.16: Schematic representation of the WAVE model calibration procedure

a) Mean Absolute Error (MAE)

The mean absolute error describes the differences between the model simulation and observations in the units of the variable (Legates and McCabe, 1999).

$$MAE = \frac{\sum_{i=1}^{n} |O_i - P_i|}{n} \qquad (6-1)$$

Optimum value = 0.0 ($0.0 \le MAE$)

Where, P_i is the ith simulated value;

O_i is the ith observed value;

n is the number of observations.

b) Relative Root Mean Square Error ($RRMSE$)

The relative root mean square RRMSE can be used as an indicator to examine the predictive ability of the model (Kim and Heo, 2002).

$$RRMSE = \sqrt{\frac{\sum_{i=1}^{n} (O_i - P_i)^2}{n}} \times \frac{1}{\bar{O}} \qquad (6-2)$$

Where, $\bar{O}$ is the average of the observed values.

Optimum value = 0.0 ($0.0 \le RRMSE$)

c) Coefficient of Efficiency (EF_2)

The coefficient of efficiency EF_2 has been widely used in the evaluation of hydrological model performance (Wilcox *et al.*, 1990; Legates and McCabe, 1999). It range from minus infinity to 1.0 $(-\infty < EF_2 \le 1.0)$. Higher than zero values indicate better agreement between observed and simulated parameters. EF_2 values less than zero mean that, the model predicted values are worse than simply using the observed mean (Elmaloglou and Malamos, 2000).

$$EF_2 = 1.0 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2} \qquad (6-3)$$

d) Coefficient of Determination (CD)

The coefficient of determination (CD) represents the ratio between the scatter of simulated value to the scatter of the measurements (Xevi *et al.,* 1996)

$$CD = \frac{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2}{\sum_{i=1}^{n}\left(P_i - \bar{O}\right)^2} \qquad (6-4)$$

Optimum value = 1.0 $(0.0 < CD \leq +\infty)$

e) Coefficient of Residual Mass (CRM):

The CRM represents the degree of underprediction or overprediction of a variable. Positive values of CRM mean that the model underestimate the measurements and negative values indicate that the model overestimate the measurements (Elmaloglou and Malamos, 2000; and Espino *et al.,* 1995).

$$CRM = \frac{\sum_{i=1}^{n}\bar{O} - \sum_{i=1}^{n}\bar{P}}{\sum_{i=1}^{n}\bar{O}} \qquad (6-5)$$

where, $\bar{P}$ is the average of the simulated values;

Optimum value = 0.0 $(-\infty < CRM \leq +\infty)$

f) Pearson type Goodness of fit index (R^2):

R^2 range is between 0 and 1.0; it can take maximum value of 1.0 with higher values indicating better agreement. The worst model fit when R^2 equals to zero (Motovilov *et al.,* 1999).

$$R^2 = \left[\frac{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)\left(P_i - \bar{P}\right)}{\sqrt{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2}\sqrt{\sum_{i=1}^{n}\left(P_i - \bar{P}\right)^2}} \right]^2 \qquad (6-6)$$

6.5.3 Fitting Soil Moisture Retention Curves

Water flow and solute transport is very sensitive to the moisture retention function $\theta(h)$, which describes the relationship between soil moisture content and pressure head. The soil moisture retention function is modelled in the WAVE model using the van Genuchten equation (4.2). A well-defined relationship between soil moisture content and soil moisture tension needs to be derived through fitting the parameters of the van Genuchten equation. This can be done using observed soil moisture tension data.

Soil moisture content and soil moisture tension relationships in the form of soil moisture retention curves, were developed at each of the pilot sites from the observed field data. These curves were conditioned by observed data of soil moisture tension and volumetric soil moisture contents at saturation and at wilting point at different depths at each pilot area. These data are summarised in Table 6.12 below. The objective has been to develop soil moisture retention curves that match the observed soil moisture data and reflect the field situation at each site. Soil moisture retention curves were fitted through a trial and error process of adjusting the α, n, and m parameters of the van Genuchten equation.

Table 6.12: Saturation and residual soil moisture contents

Soil layer (cm)	Makhtali		Birlik		Karaoi	
	θ_s	θ_r	θ_s	θ_r	θ_s	θ_r
0 – 20	46.2	9.3	47.2	8.4	46.5	7.7
21 – 40	36.5	9.3	37.5	8.4	43.0	7.7
41 – 60	41.3	9.3	45.0	8.4	44.6	7.7
61 – 80	42.9	9.3	46.7	8.4	47.2	7.7
81 – 100	44.4	9.3	46.8	8.4	47.2	7.7
101 – 150	44.6	9.3	46.6	8.4	46.8	7.7
151 – 200	44.8	9.3	45.0	8.4	45.5	7.7
201 – 250	45.0	9.3	43.6	8.4	44.7	7.7
251 - 300	44.1	9.3	43.3	8.4	44.9	7.7

Source: Mott MacDonald, (2003b)

The soil moisture content and soil moisture tension data recorded at different depths for each of the pilot areas are plotted in Figures 6.17 to 6.22 along with the fitted retention curves. The trial and error process showed that the soil moisture retention curve is more sensitive to the parameter α than other parameters. The parameters for the fitted retention curves are given in Table 6.13. These parameter values were used as initial values in the WAVE_MS model calibration.

It is clear from Figures 6.17 to 6.22 that the quality of much of the soil moisture and soil moisture tension data is poor, and that it lacks consistency. The observed data should lie on a well defined relationship, but generally do not. The data are also available only for a relatively narrow range, with no data close to either saturation or wilting points. It is understood that equipment was late in arriving on site, and that this led to difficulties in calibrating equipment and resulted in very low and very high soil moisture contents being missed. The fitted soil moisture retention curves were adapted to pass through the available data at each site as well as possible. There are problems in the observed soil moisture tension data at many depths as there is a wide scatter between observed soil moisture tension data at the same moisture content. More discussion about the reliability of the observed soil moisture tension data is included in section 6.5.5 below.

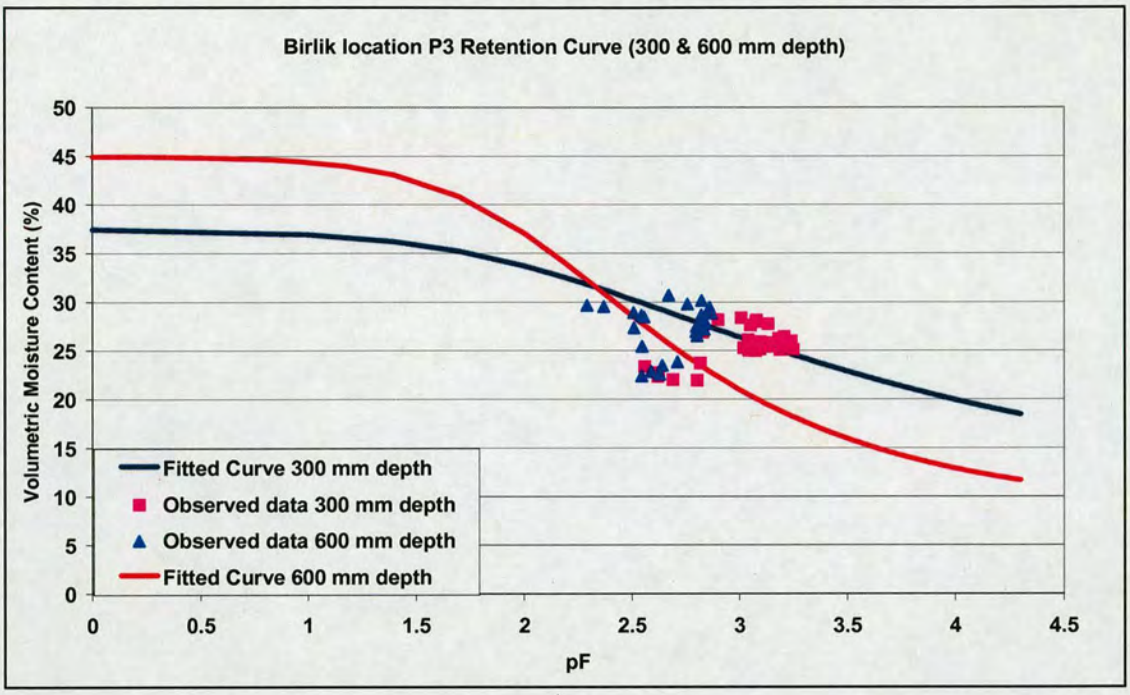


Figure 6.17: Soil moisture retention curve, Birlik, location P3, 300 and 600 mm depth

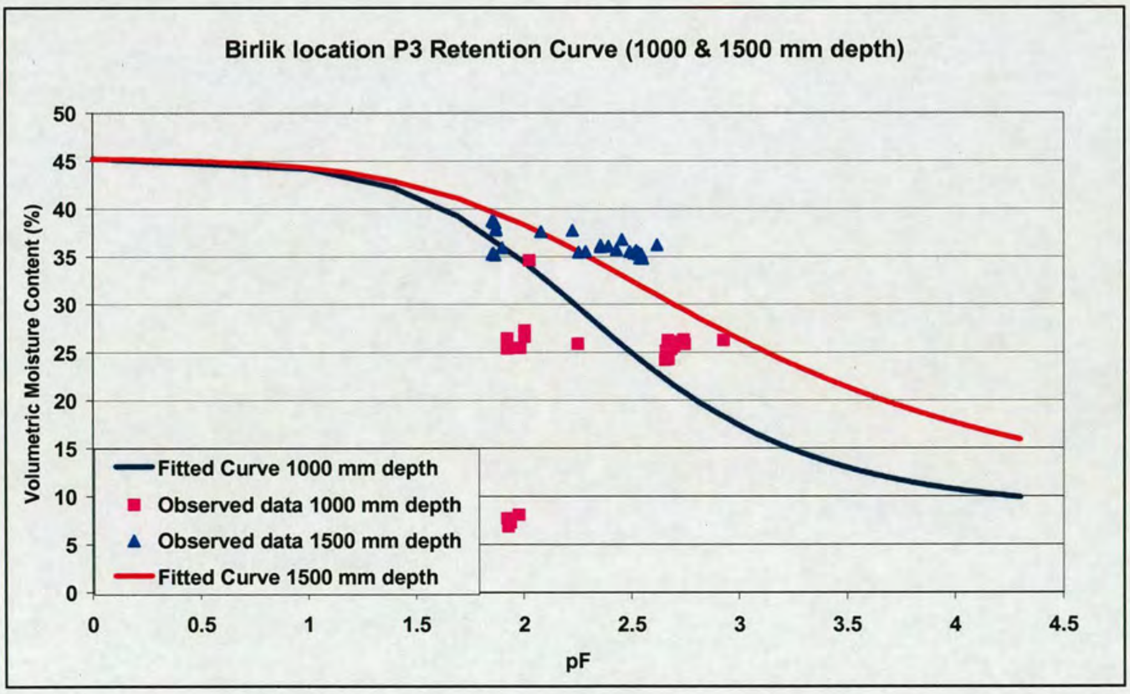


Figure 6.18: Soil moisture retention curve, Birlik, location P3, 1000 and 1500 mm depth

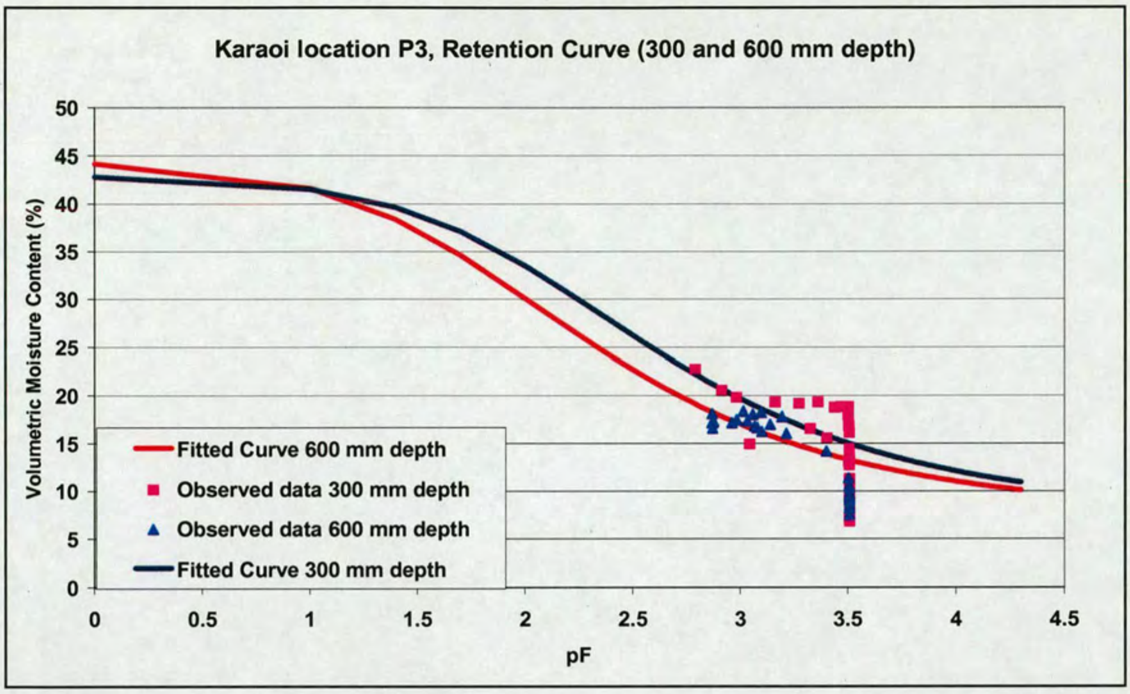


Figure 6.19: Soil moisture retention curve, Karaoi, location P3, 300 and 600 mm depth

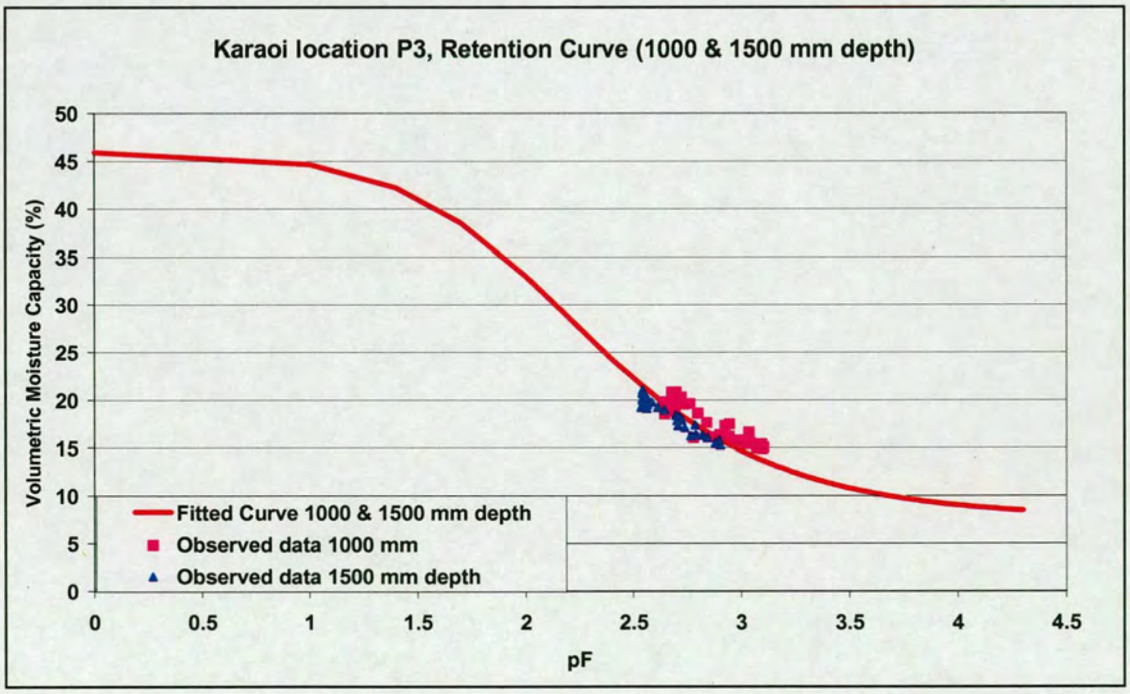


Figure 6.20: Soil moisture retention curve, Karaoi, location P3, 1000 and 1500 mm depth

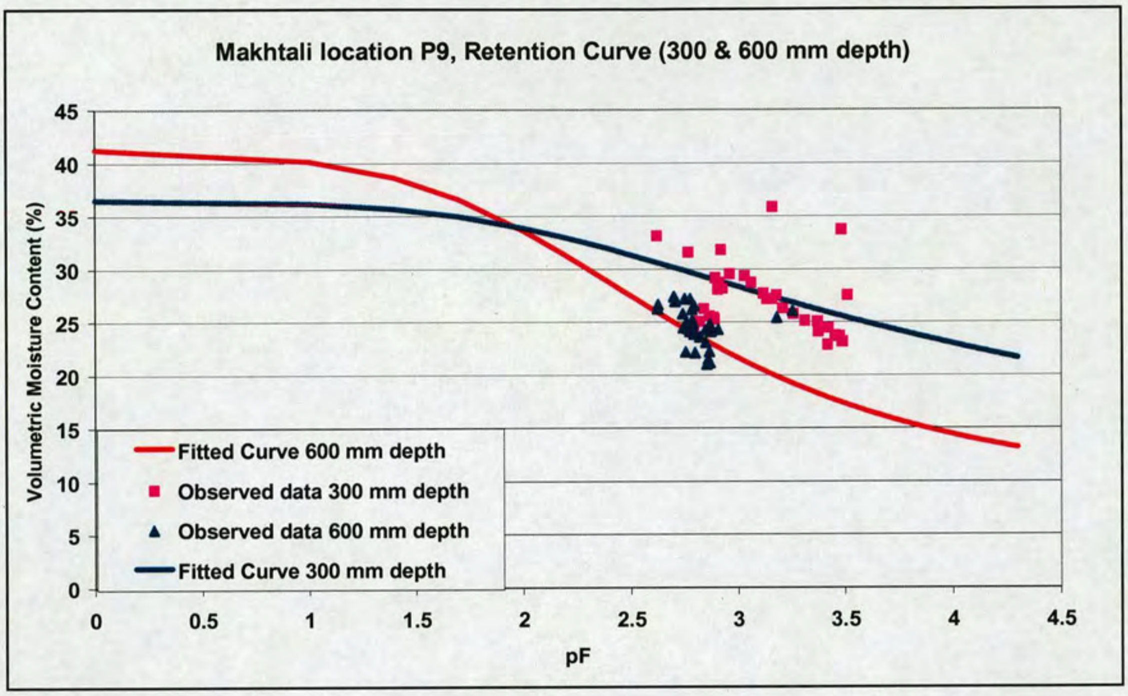


Figure 6.21: Soil moisture retention curve, Makhtali, location P9, 300 and 600 mm depth.

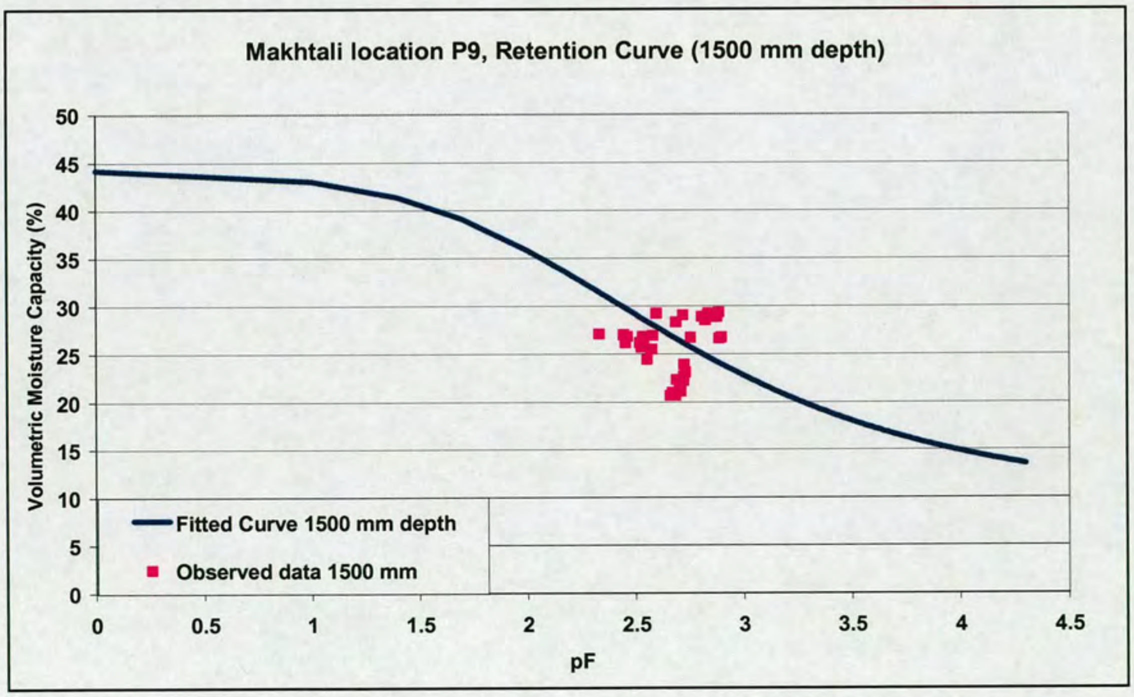


Figure 6.22: Soil moisture retention curve, Makhtali, location P9, 1500 mm depth

Table 6.13: Fitted soil moisture retention curve parameters

Pilot Area	Depth mm	Parameter		
		α	n	m
	300	0.01	1	0.15
Makhtali, location P9	600	0.01	1	0.4
	1500	0.01	1	0.4
	300	0.01	1	0.2
Birlik, location P3	600	0.01	1.3	0.35
	1000	0.01	1.2	0.5
	1500	0.01	1	0.3
	300	0.01	1	0.5
Karaoi, location P6	600	0.02	1	0.5
	1000	0.01	1.2	0.6
	1500	0.01	1.2	0.6

6.5.4 Soil Moisture Content Calibration

Following preliminary fitting of the soil moisture retention curve characteristics to the observed data, calibration of these parameters was carried out with WAVE_MS through matching observed and simulated soil moisture content. Using the parameter values presented in Table 6.13, large differences were found between observed and simulated soil moisture content at some depths especially in the top soil layers where simulated soil moisture content was often higher than observed (Figures 6.23 and 6.24). However, simulated soil moisture contents fit well with those observed at many depths at the locations under consideration (Figures 6.25 and 6.26), and only small differences were found at some other depths (Figures 6.27 to 6.30) with patterns of changing soil moisture being reasonably simulated.

There are some issues related to data quality. For example, in early March following leaching, soil moisture content should be close to saturation. At Makhtali and Karaoi observed soil moisture content in this period was around 30% at Makhtali and 25% and Karaoi. The problem is thought most likely to be associated with sampling errors, particularly during 2002 data collection programme. In 2002 soil moisture was measured using automatic soil monitoring equipment and gravimetric laboratory analysis at a large number of sites in each pilot area. However, problems associated with the data obtained from both the soil monitoring equipment and from gravimetric soil moisture analysis were reported in the evaluation of the soil monitoring equipment results (Mott MacDonald, 2003b). Sample sizes for gravimetric measurements were smaller than standard, and calibration of some of the automatic equipment may have been based on incorrect gravimetric data.

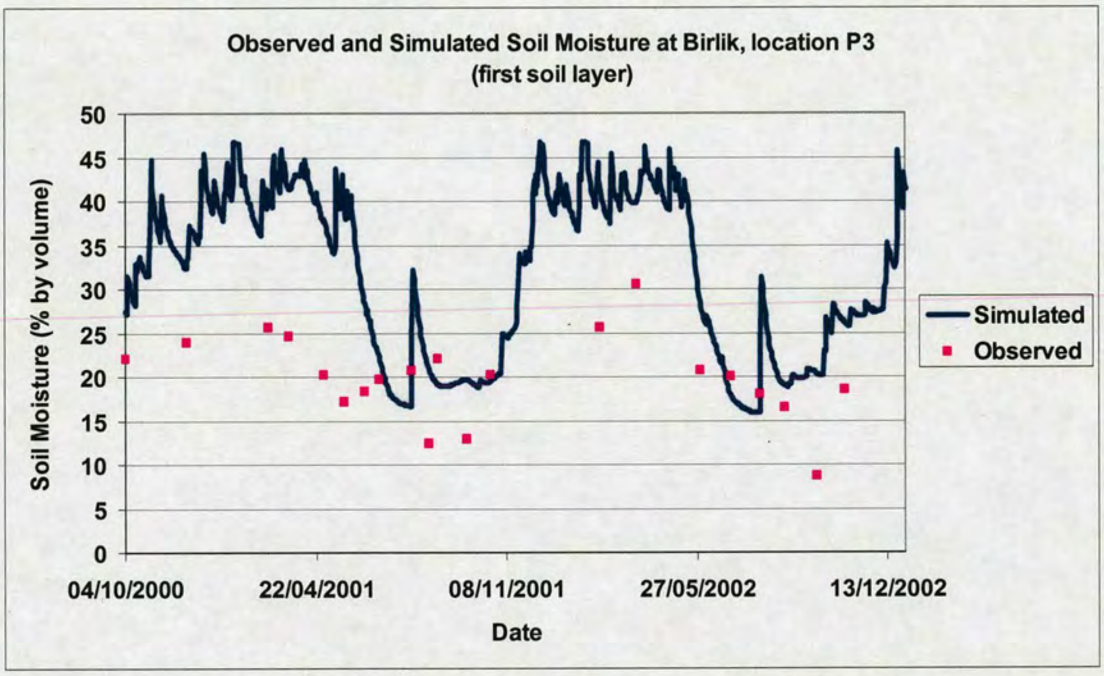


Figure 6.23: Birlik, location P3 Initial Run–Soil Moisture 0-200 mm

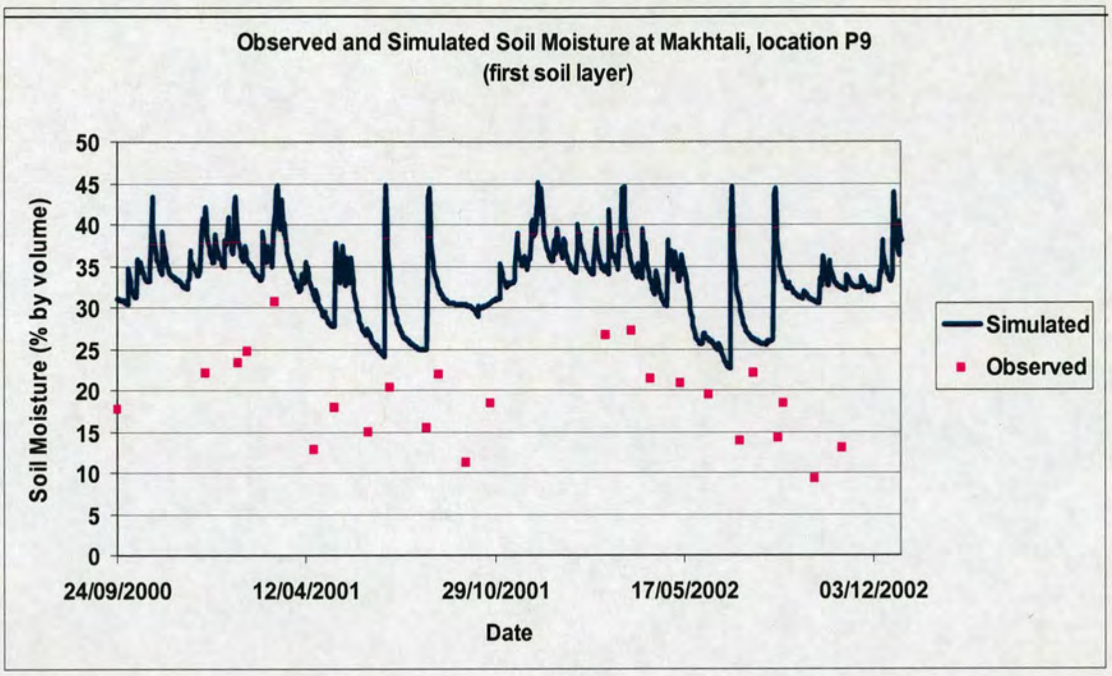


Figure 6.24: Makhtali, location P9 Initial Run–Soil Moisture 0-200 mm

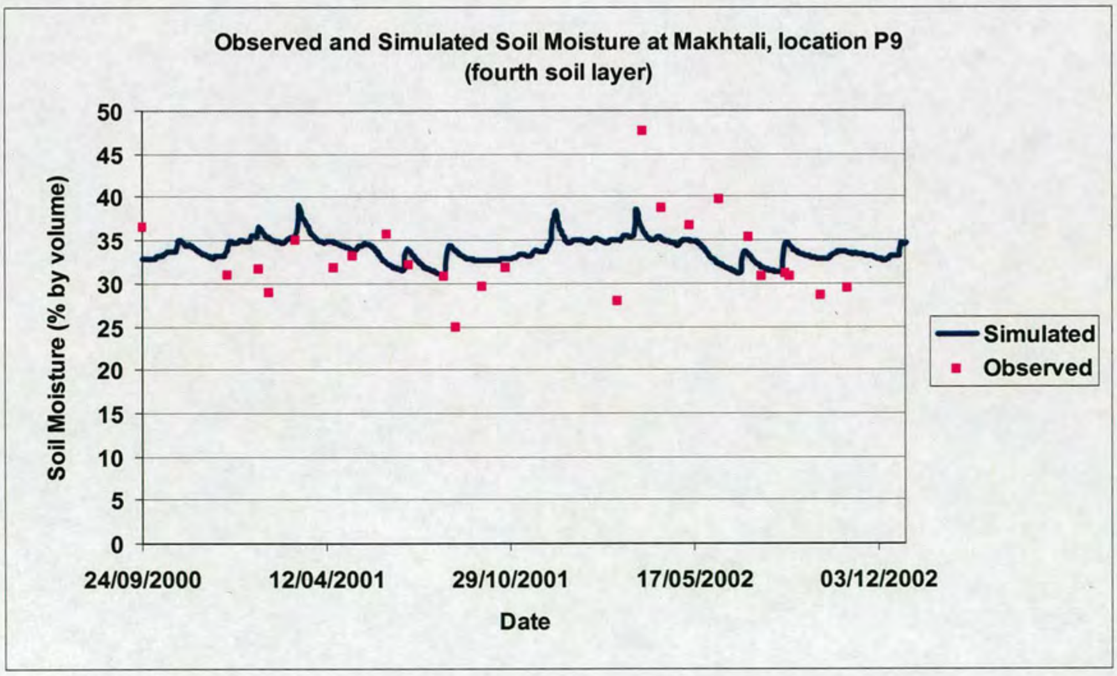


Figure 6.25: Makhtali, location P9 Initial Run–Soil Moisture 600-8000 mm

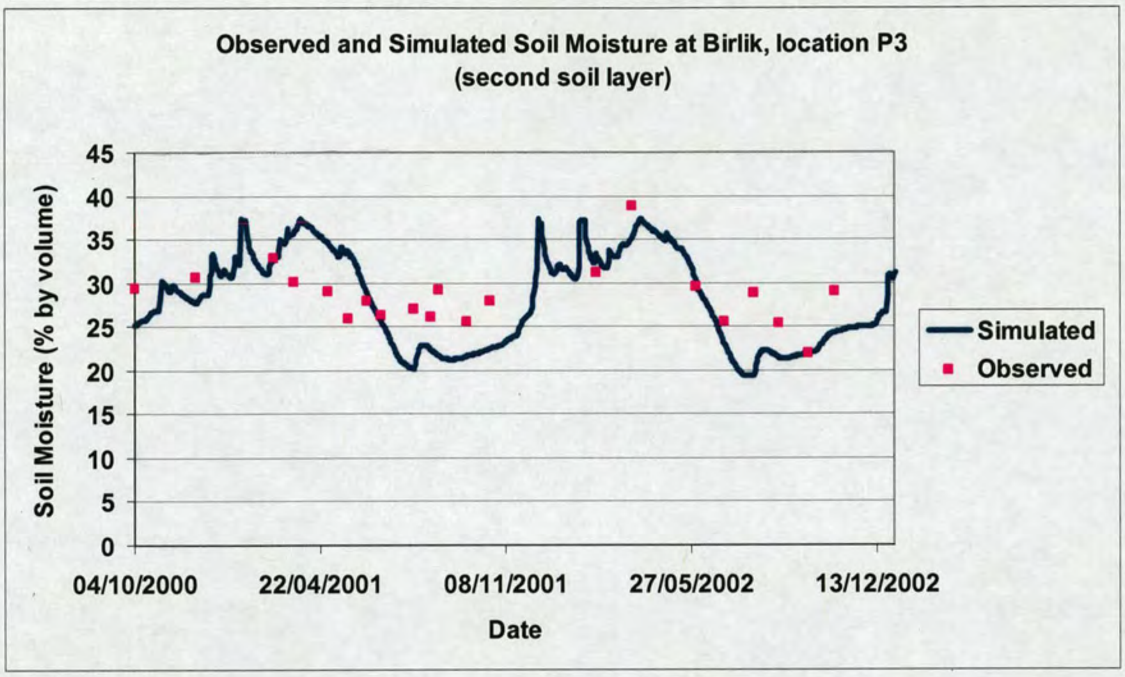


Figure 6.26: Birlik, location P3 Initial Run–Soil Moisture 200-400 mm

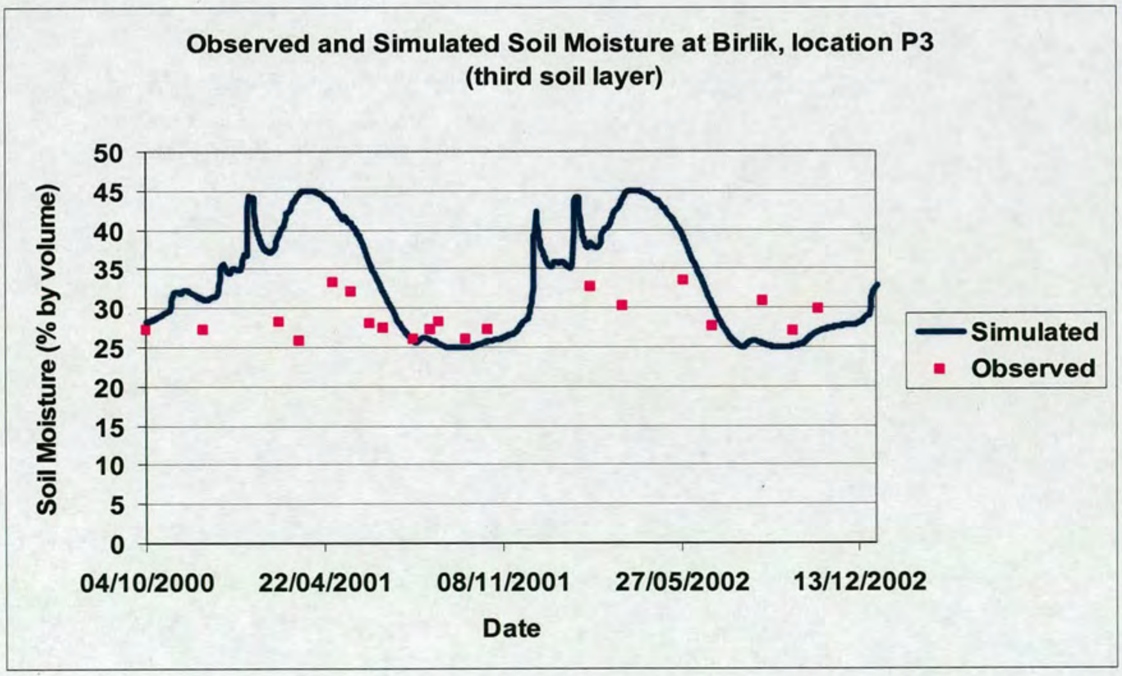


Figure 6.27: Birlik, location P3 Initial Run–Soil Moisture 400-600 mm

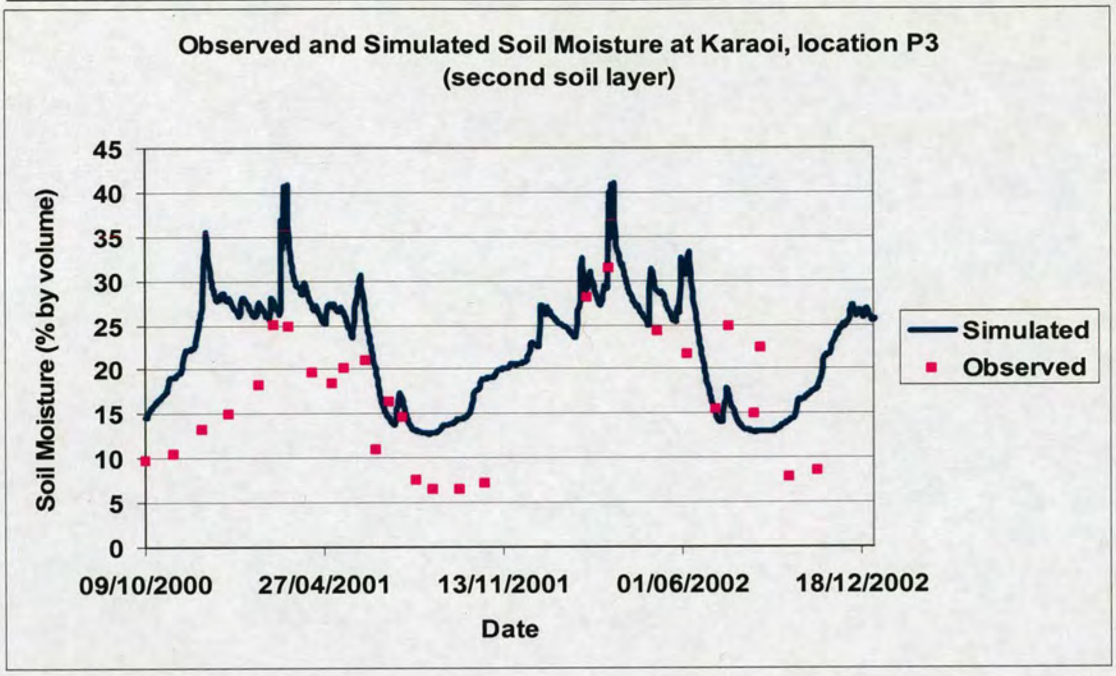


Figure 6.28: Karaoi, location P3 Initial Run–Soil Moisture 200-400 mm

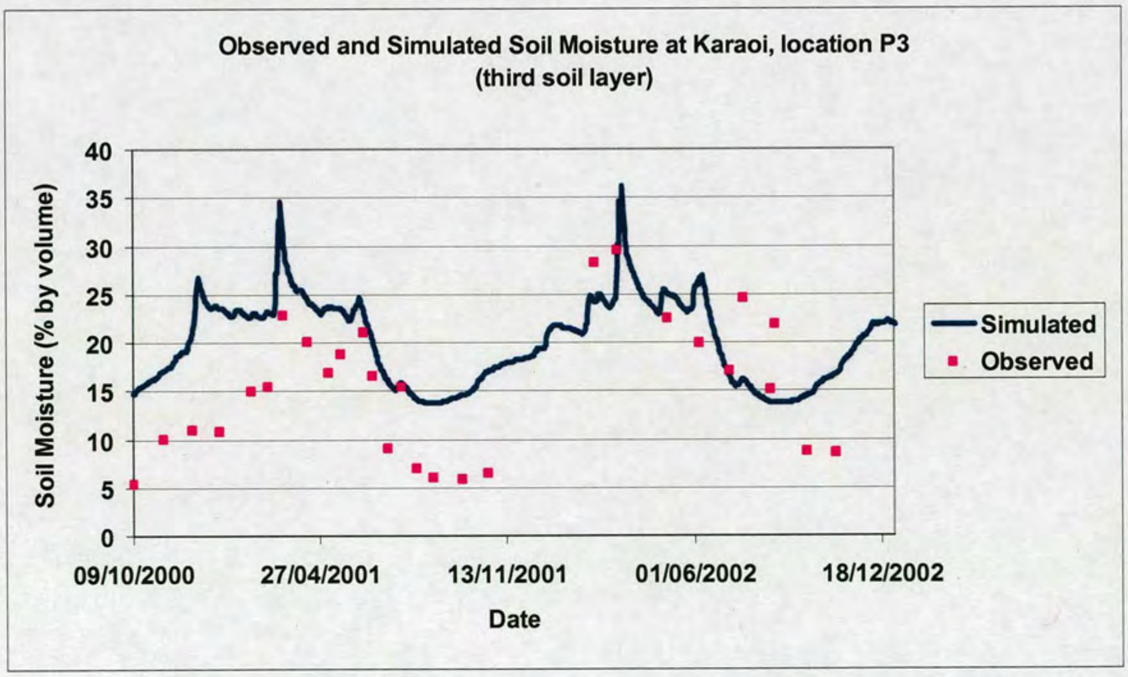


Figure 6.29: Karaoi, location P3 Initial Run–Soil Moisture 400-600 mm

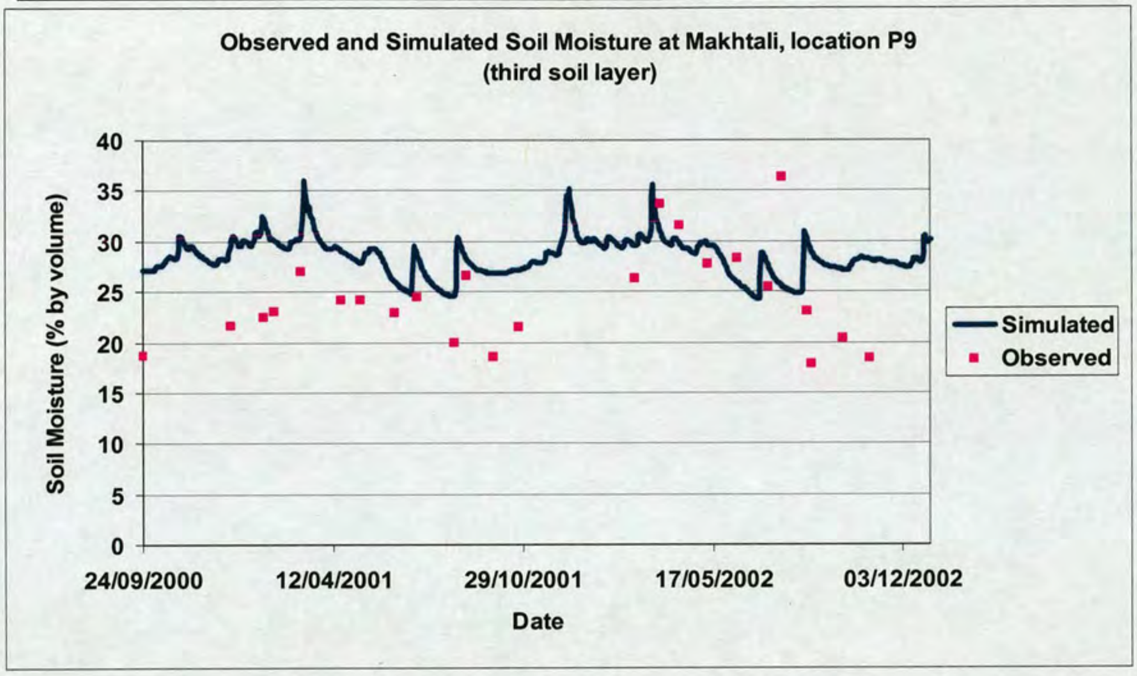


Figure 6.30: Makhtali, location P9 Initial Run–Soil Moisture 400-600 mm

Recognising that there have potentially been errors in soil moisture content measurement, and the soil moisture tension measurements used to derive the moisture retention curves, the soil moisture retention parameters were adjusted to improve the WAVE_MS model performance in simulating soil moisture. A series of model runs was carried out for the two years of observed soil moisture content data. In these runs the values of parameters used in the soil moisture retention and hydraulic conductivity equations (θ_s, θ_r, α, m, and n) were modified in a trial and error process to determine values that permitted reasonable simulation of the observed soil moisture data. In these runs observed groundwater levels were used as the lower boundary condition for the model.

By modifying the soil moisture retention parameters described above, the simulated soil moisture content could match quite well with that observed in the four soil layers examined at most sites in the project area. Figures 6.31 to 6.36 are typical examples and show good agreement between observed and simulated soil moisture for the two years of observations available.

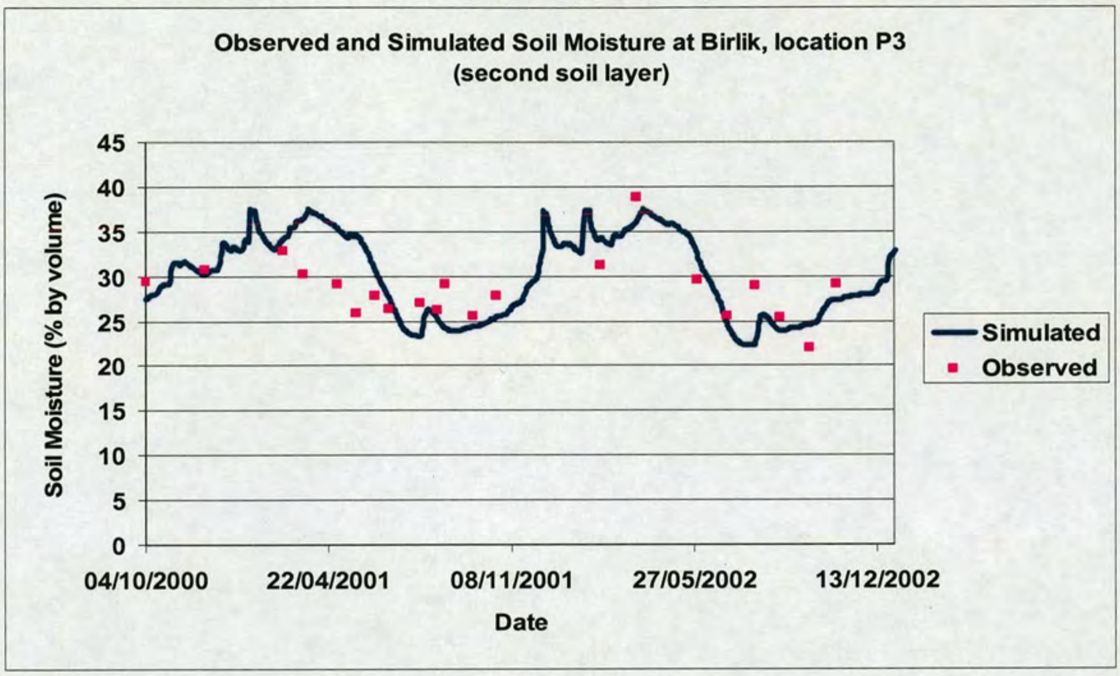


Figure 6.31: Birlik, location P3 Calibration Run–Soil Moisture 200-400 mm

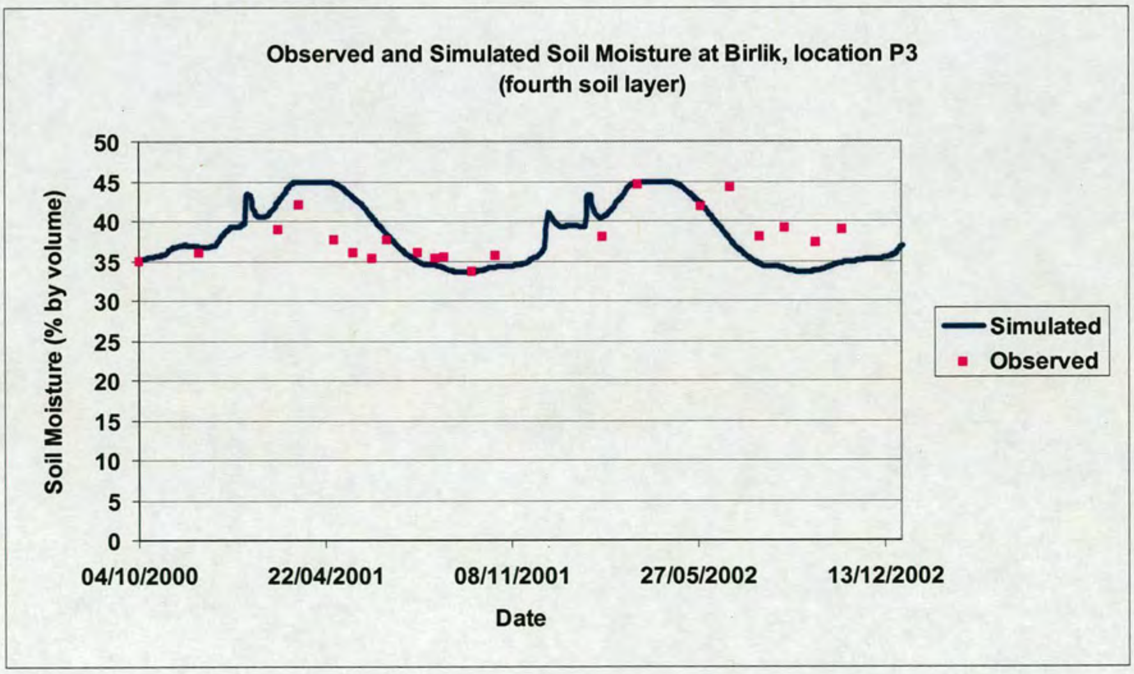


Figure 6.32: Birlik, location P3 Calibration Run–Soil Moisture 600-8000 mm

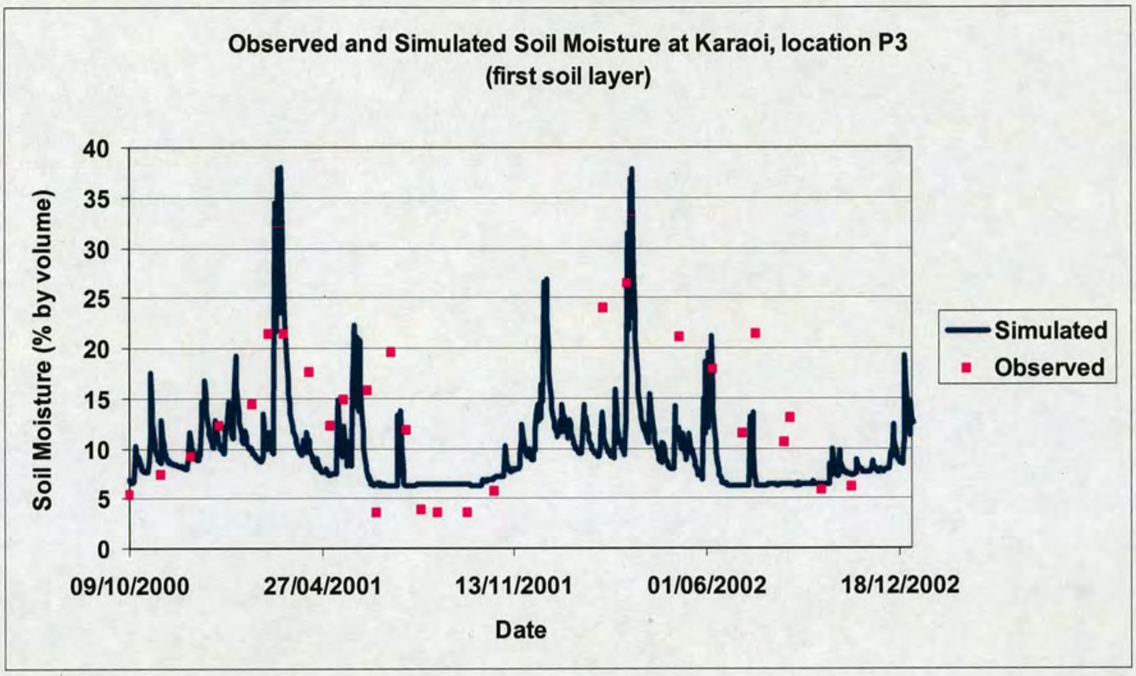


Figure 6.33: Karaoi, location P3 Calibration Run–Soil Moisture 0-200 mm

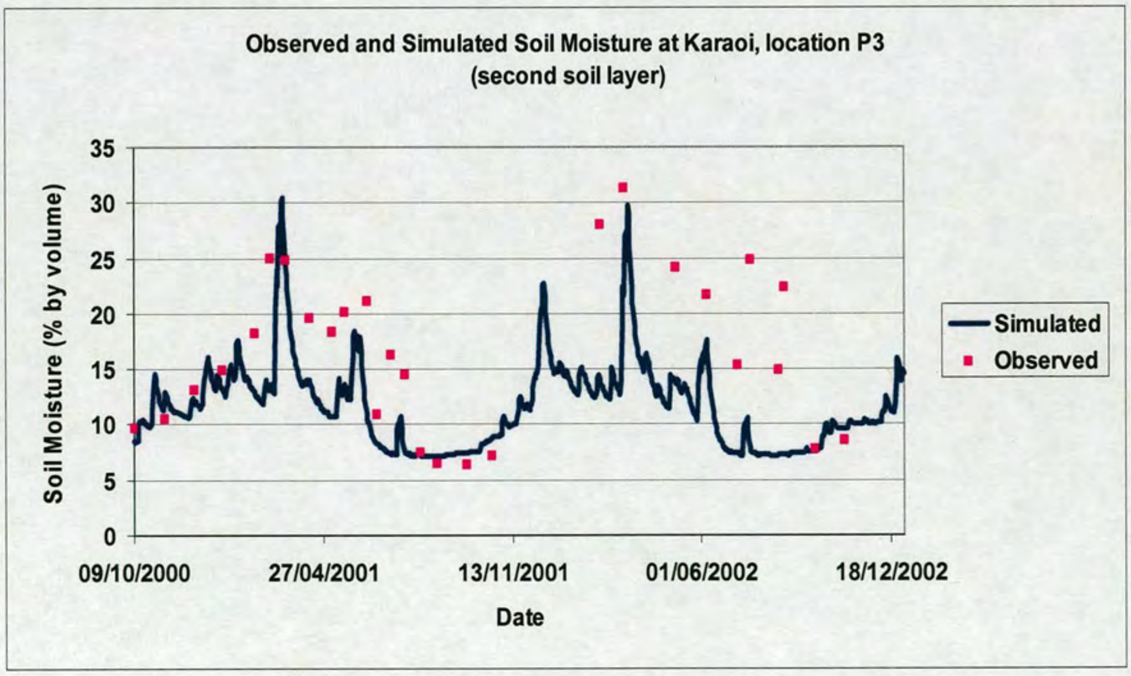


Figure 6.34: Karaoi, location P3 Calibration Run–Soil Moisture 200-400 mm

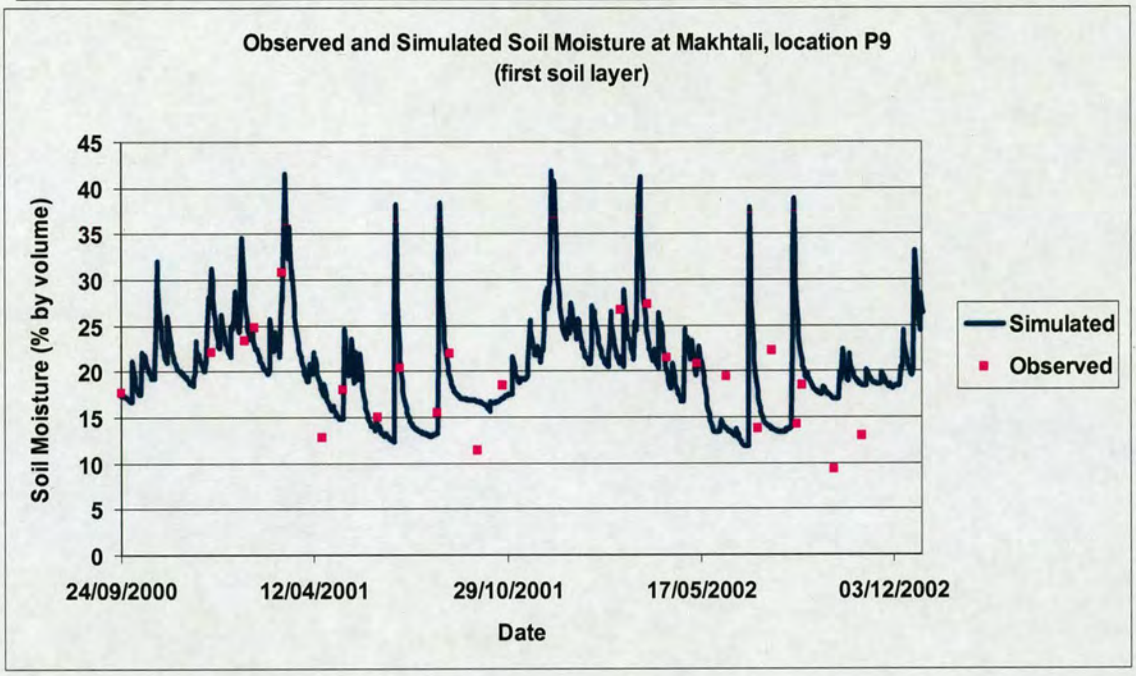


Figure 6.35: Makhtali, location P9 Calibration Run–Soil Moisture 0-200 mm

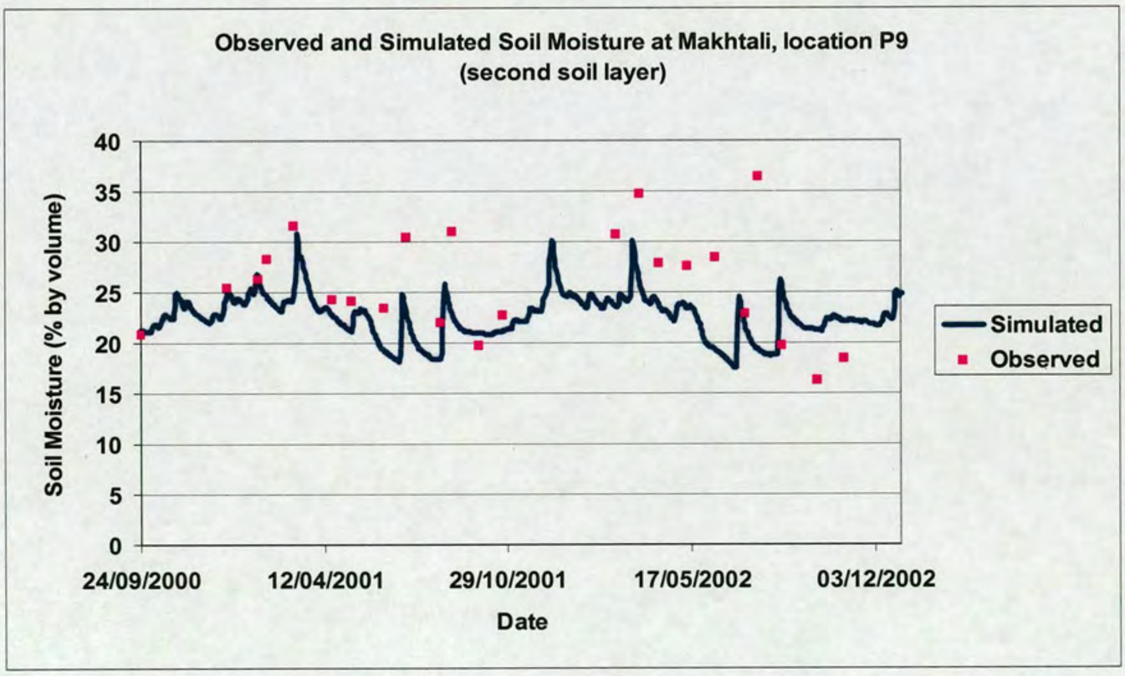


Figure 6.36: Makhtali, location P9 Calibration Run–Soil Moisture 400-600 mm

Table 6.14 presents the results of the statistical tests used to assess calibration quality. Generally, the modified WAVE model has satisfactorily simulated soil moisture content at all locations under consideration. The statistical indices show a reasonable model performance in predicting soil moisture content. R^2 ranged between 0.36 and 0.75 in most depths within the areas under consideration. In the calibration of soil moisture content using ECOMAG model which describes the processes of soil infiltration, evapotranspiration, soil water content, surface and subsurface flow and groundwater flow, Motovilov *et al.* (1999) considered that simulation results are considered to be good for values of $R^2 \geq 0.75$, and satisfactory for R^2 between 0.36 and 0.75. In addition, the values of the coefficient of efficiency EF_2 and the coefficient of determination CD, ranged between -0.08 and 0.66; 0.12 and 0.98 respectively which are reasonably close the optimum value of 1.0 at most sites. The coefficient of residual mass CRM show that the model predicted soil moisture content with minimum overestimation or underestimation in most sites.

The calibrated values of the soil moisture retention parameters for each of the sites modelled are summarised in Table 6.15. The calibrated soil moisture retention parameters $(\theta_s, \theta_r, \alpha, m, and \quad n)$, result in re-defined soil moisture retention curves. These are shown in Figures 6.37 to 6.40. With the exception of the surface layers at Makhtali, the curves still represent the data reasonably well. It is known that a high water table at Birlik certainly caused problems with some of the automatic equipment in 2002, but the reason for the large discrepancy in the 300 *mm* and 600 *mm* depth layers at Makhtali are not clear (Figure 6.38). There are clearly discrepancies between the soil moisture content and soil moisture tension data at this site.

Table 6.14: Values of the statistical parameters used in the comparison of soil moisture content

Pilot Area	Layer	*MAE*	*RRMSE*	EF_2	*CD*	*CRM*	R^2
Birlik-P3	1	5.54	0.36	-1.15	0.29	-0.03	0.38
	2	3.01	0.13	-0.25	0.50	-0.01	0.38
	3	4.10	0.19	-4.41	0.12	-0.06	0.45
	4	2.41	0.08	-0.16	0.51	0.01	0.41
Birlik-P12	1	6.1	0.35	-1.9	0.19	0.01	0.51
	2	3.7	0.17	-0.47	0.44	0.07	0.41
	3	5.1	0.23	-2.5	0.19	0.07	0.38
	4	3.7	0.12	0.18	0.89	0.05	0.43
Makhtali-P3	1	2.7	0.19	0.08	0.59	0.02	0.47
	2	2.7	0.17	-0.57	1.1	0.09	0.06
	3	3.7	0.15	-0.7	0.92	0.09	0.07
	4	2.2	0.08	0.24	6.9	0.02	0.39
Makhtali-P9	1	3.30	0.20	0.39	1.36	0.03	0.43
	2	3.52	0.17	0.14	1.86	0.09	0.37
	3	2.52	0.13	0.38	2.91	-0.01	0.39
	4	2.46	0.10	0.14	2.55	0.02	0.39
Makhtali-P15	1	4.1	0.39	-0.5	0.52	-0.19	0.32
	2	3.2	0.18	0.11	1.11	0.06	0.32
	3	4.6	0.26	0.09	1.6	0.13	0.33
	4	4.6	0.14	-0.72	1.9	-0.04	0.31
Karaoi-P3	1	3.11	0.35	0.66	1.44	0.1	0.69
	2	5.44	0.50	-0.09	0.98	0.33	0.40
	3	3.50	0.36	0.27	2.06	0.17	0.43
	4	2.63	0.13	-0.08	0.53	0.01	0.43
Karaoi-P6	1	3.04	0.33	0.7	1.83	0.1	0.75
	2	3.85	0.42	0.4	1.23	0.18	0.33
	3	3.0	0.31	0.62	3.1	0.07	0.73
	4	3.0	0.2	0.25	1.0	-0.02	0.39

Table 6.15 Final Calibration Parameters

Pilot Area	Location	Layer	Depth	MRC Parameters					HCC Parameters	
				θ_r	θ_s	α	n	m	B	N
Makhtali	P3	1	0-200	9	46	0.03	1.5	0.4	0.34	1.5
		2	200-400	9	37	0.02	1.3	0.3	0.34	1.5
		3	400-600	9	41	0.02	1.2	0.4	0.34	1.5
		4	600-8000	9	44	0.01	0.8	0.3	0.34	1.5
Makhtali	P9	1	0-200	9	46	0.03	1.4	0.4	0.34	1.5
		2	200-400	9	37	0.02	1.3	0.3	0.34	1.5
		3	400-600	9	41	0.02	1.2	0.4	0.34	1.5
		4	600-8000	9	44	0.01	1.0	0.35	0.34	1.5
Makhtali	P15	1	0-200	9	44	0.03	1.3	0.4	0.34	1.5
		2	200-400	9	46	0.03	1.4	0.3	0.34	1.5
		3	400-600	9	37	0.03	1.4	0.4	0.34	1.5
		4	600-8000	9	41	0.01	0.8	0.3	0.34	1.5
Karaoi	P3	1	0-200	7	44	0.05	1.6	0.6	0.34	1.5
		2	200-400	7	43	0.04	1.5	0.5	0.34	1.5
		3	400-600	7	45	0.05	1.4	0.5	0.34	1.5
		4	600-8000	7	46	0.01	1.1	0.4	0.34	1.5
Karaoi	P6	1	0-200	7	47	0.06	1.6	0.5	0.34	1.5
		2	200-400	7	43	0.04	1.5	0.5	0.34	1.5
		3	400-600	7	45	0.05	1.4	0.5	0.34	1.5
		4	600-8000	7	46	0.01	1.1	0.4	0.34	1.5
Birlik	P3	1	0-200	8	47	0.01	1.0	0.4	0.34	1.5
		2	200-400	8	38	0.004	1.0	0.4	0.34	1.5
		3	400-600	8	45	0.01	1.0	0.4	0.34	1.5
		4	600-8000	8	45	0.004	1.0	0.4	0.34	1.5
Birlik	P12	1	0-200	8	47	0.02	1.2	0.4	0.34	1.5
		2	200-400	8	38	0.01	0.8	0.4	0.34	1.5
		3	400-600	8	45	0.02	1.2	0.4	0.34	1.5
		4	600-8000	8	45	0.01	0.7	0.4	0.34	1.5

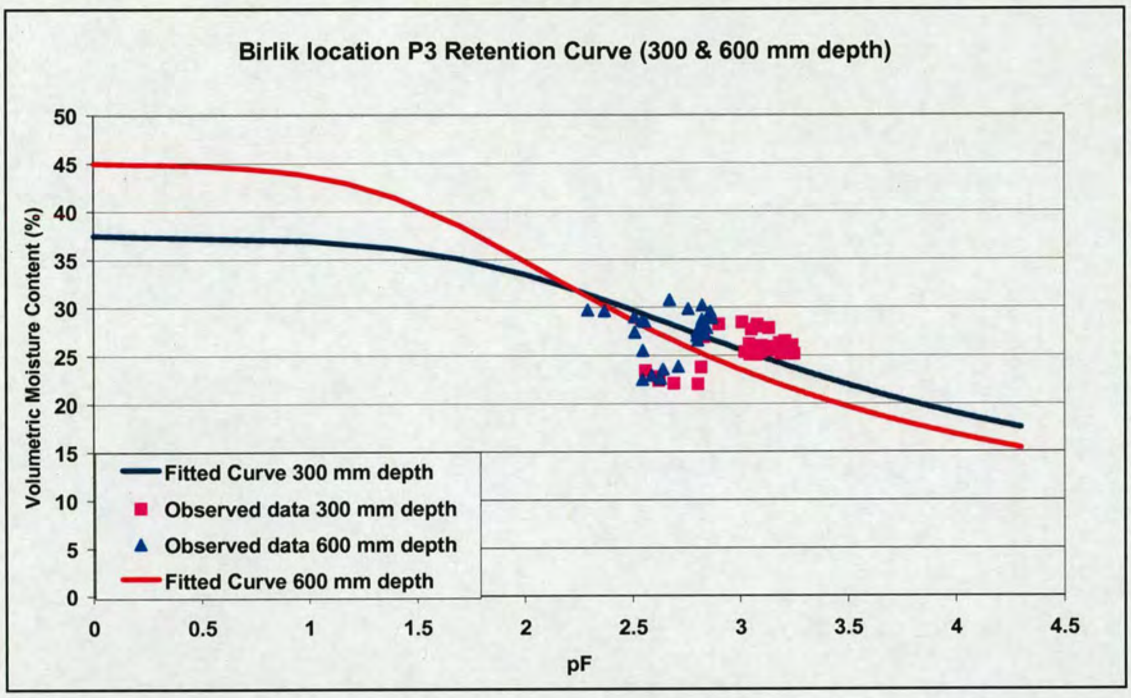


Figure 6.37: Birlik, location P3 Calibration Run–Soil Moisture Retention Curve, 300 & 600 mm depth

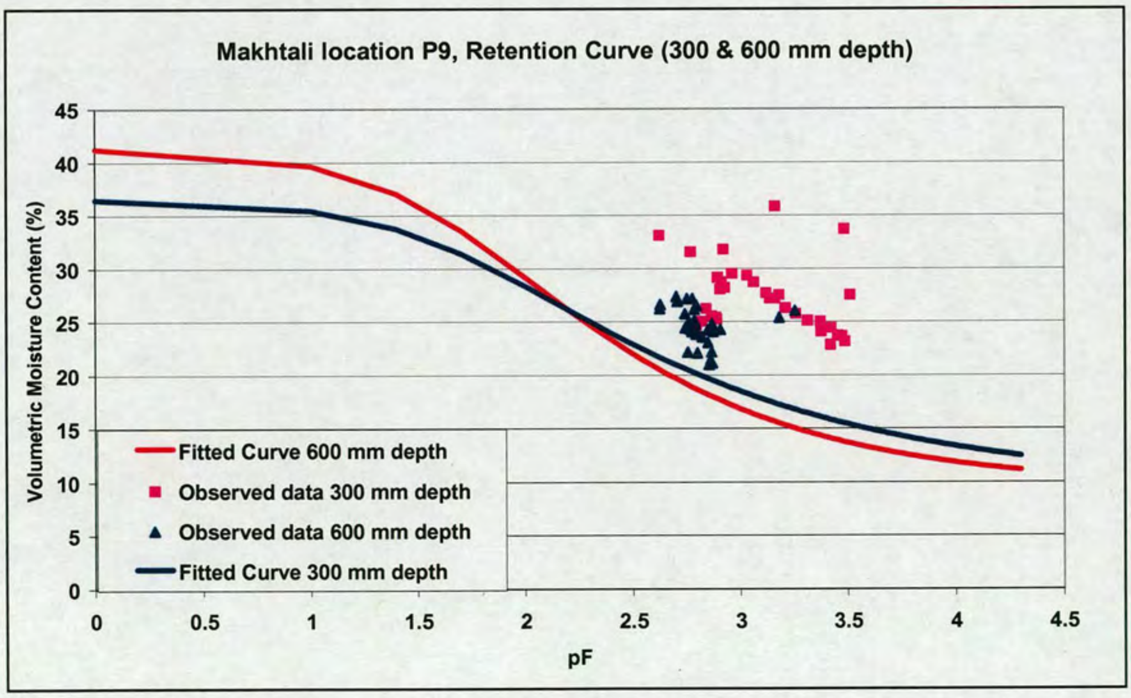


Figure 6.38: Makhtali, location P9 Calibration Run–Soil Moisture Retention Curve, 300 & 600 mm depth

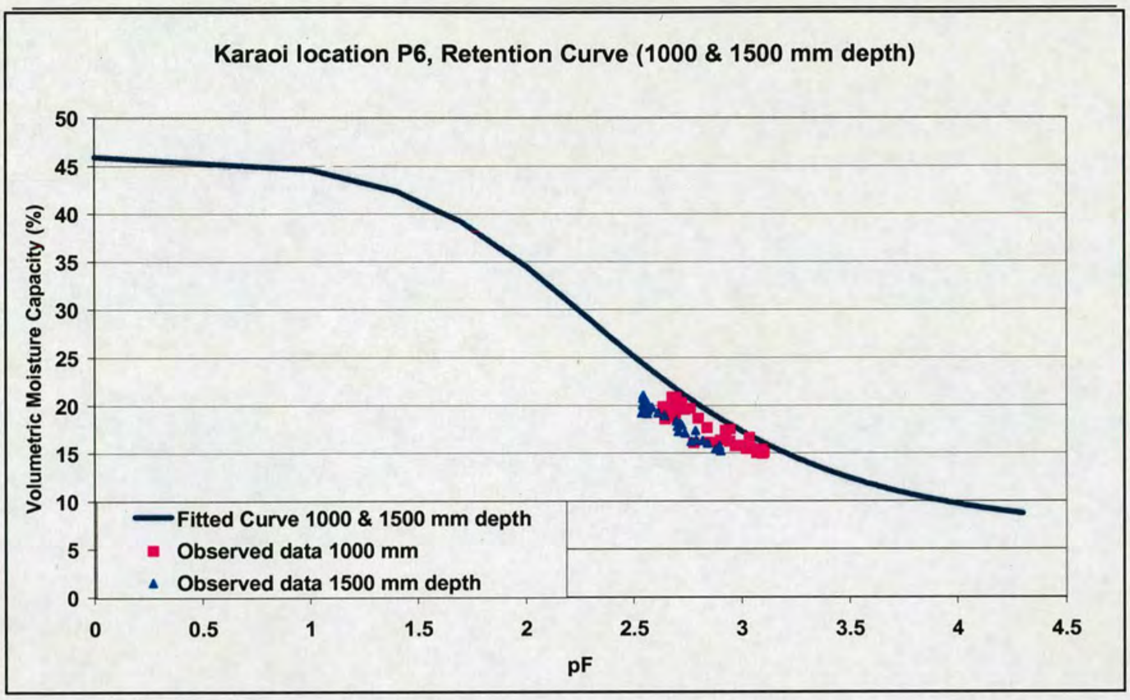


Figure 6.39: Karaoi, location P6 Calibration Run–Soil Moisture Retention Curve, 300 mm depth

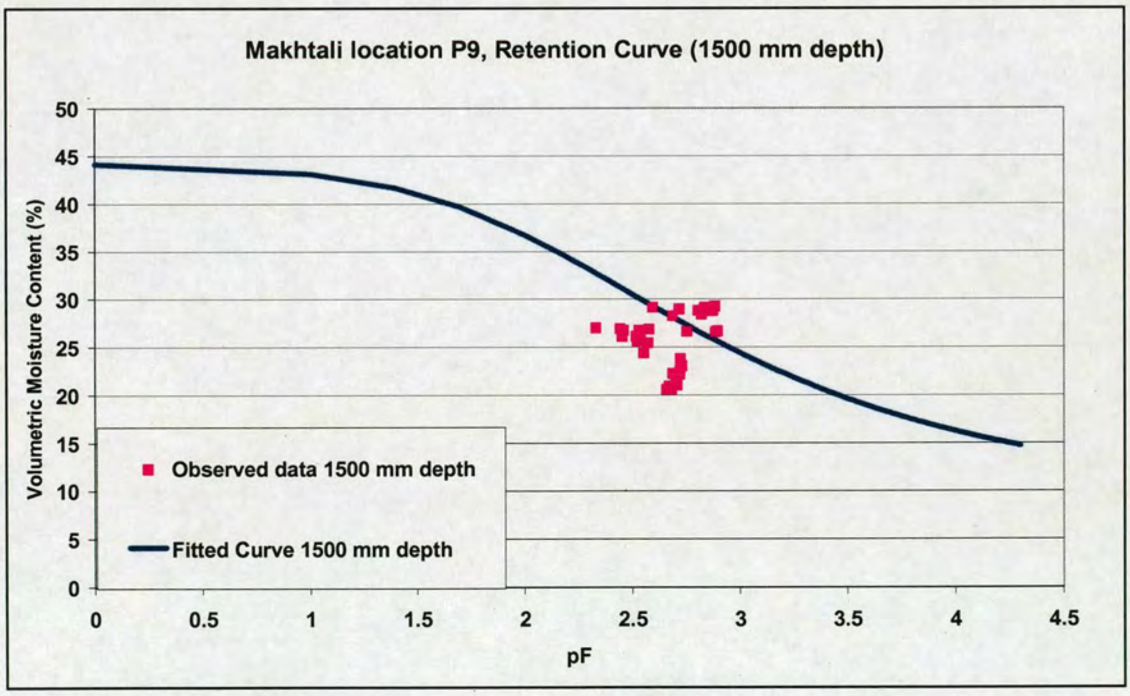


Figure 6.40: Makhtali, location P9 Calibration Run–Soil Moisture Retention Curve, 1500 mm depth

A comparison has also been made between the WAVE and WAVE_MS models in simulating soil moisture content. Over the two year period of simulation used in calibration, the differences in soil moisture content simulated using the two versions were not high as the differences in actual crop transpiration simulated using the two model versions were small. Soil moisture contents simulated with WAVE_MS was a bit higher than that simulated using the original WAVE model (Figures 6.41 to 6.43). The reason is that, the soil salinity within the two years simulation period was only slightly higher than the threshold values for crop salinity stress at Birlik and Makhtali, and very marginally above the threshold in the top soil layer at Karaoi. The relatively slow build up of salinity over the simulation period can be attributed to the annual leaching of salts. In addition, the amount of salts added through water application is relatively small because of inadequate irrigation. In Karaoi where the salinity level is under the threshold value in all but the top layer in summer, there were no significant differences in soil moisture between the two versions (Figures 6.44 and 6.45).

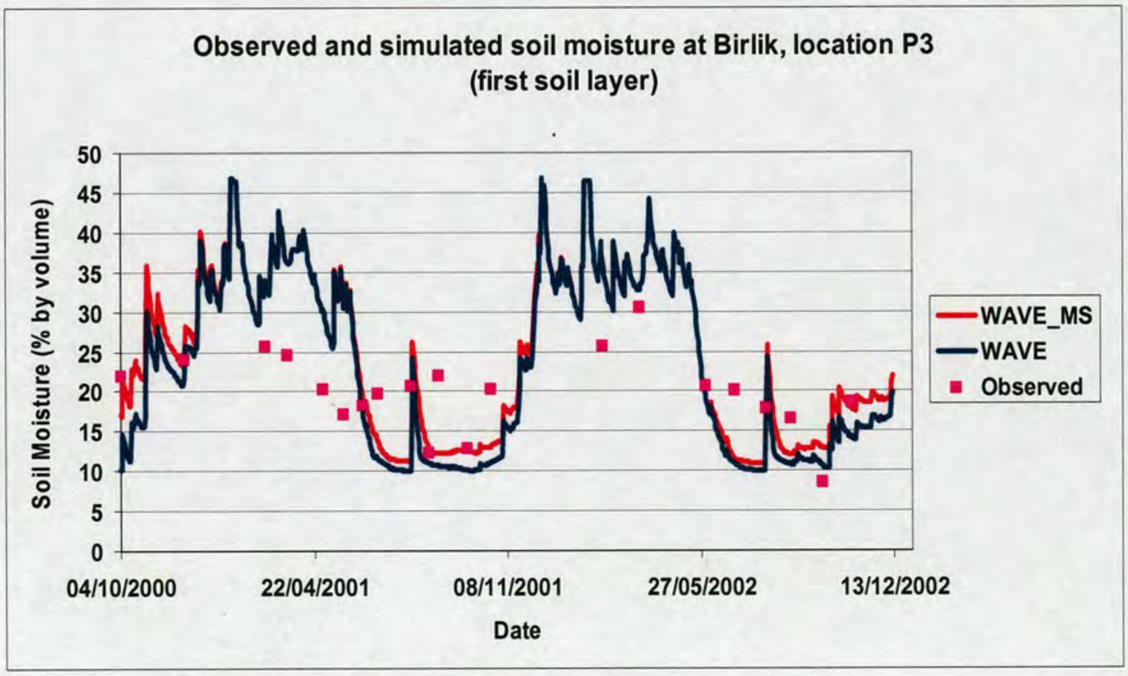


Figure 6.41: Soil moisture simulated using the WAVE and WAVE_MS models, Birlik, location P3 (0-200 mm depth)

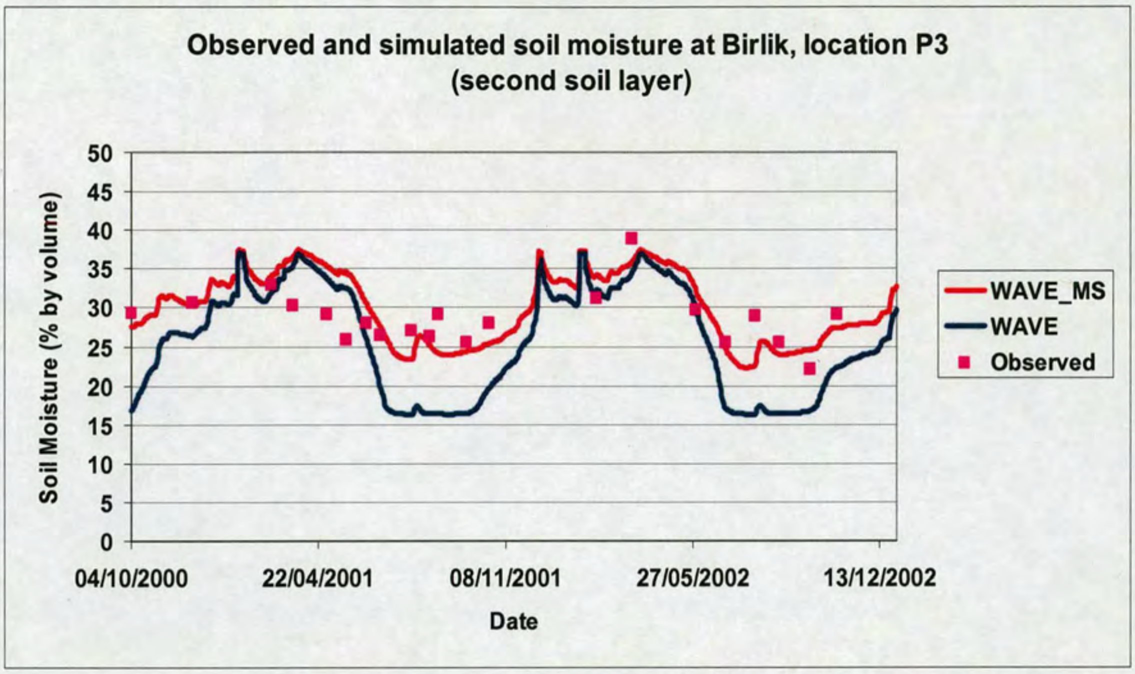


Figure 6.42: Soil moisture simulated using the WAVE and WAVE_MS models, Birlik, location P3 (200-400 mm depth)

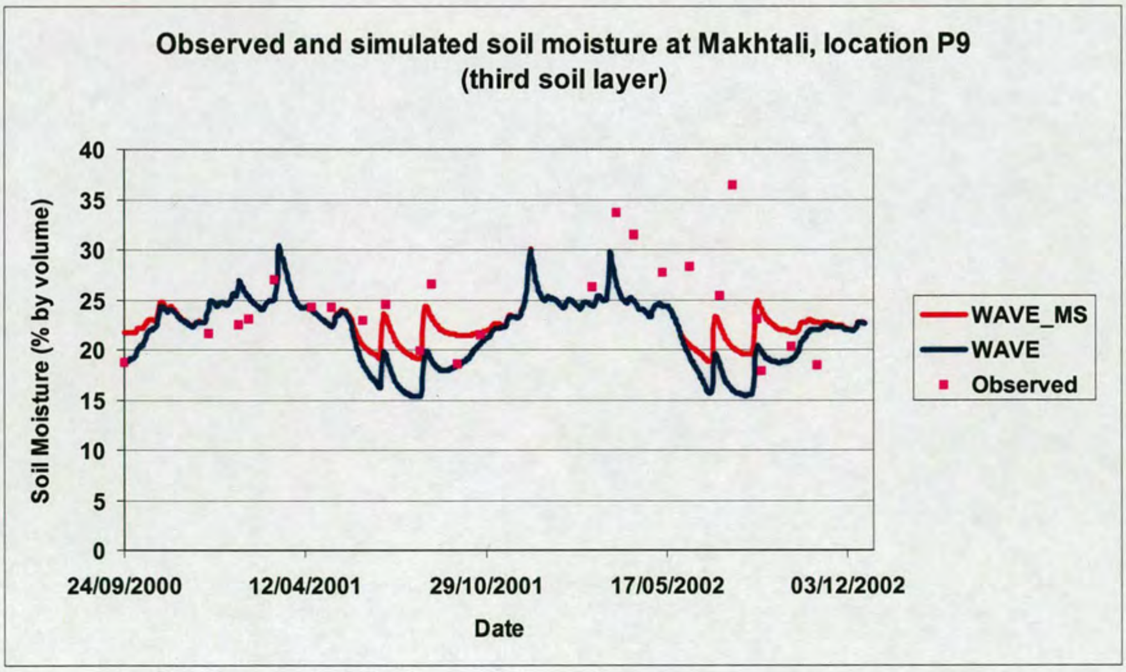


Figure 6.43: Soil moisture simulated using the WAVE and WAVE_MS models, Makhtali, location P9 (400-600 mm depth)

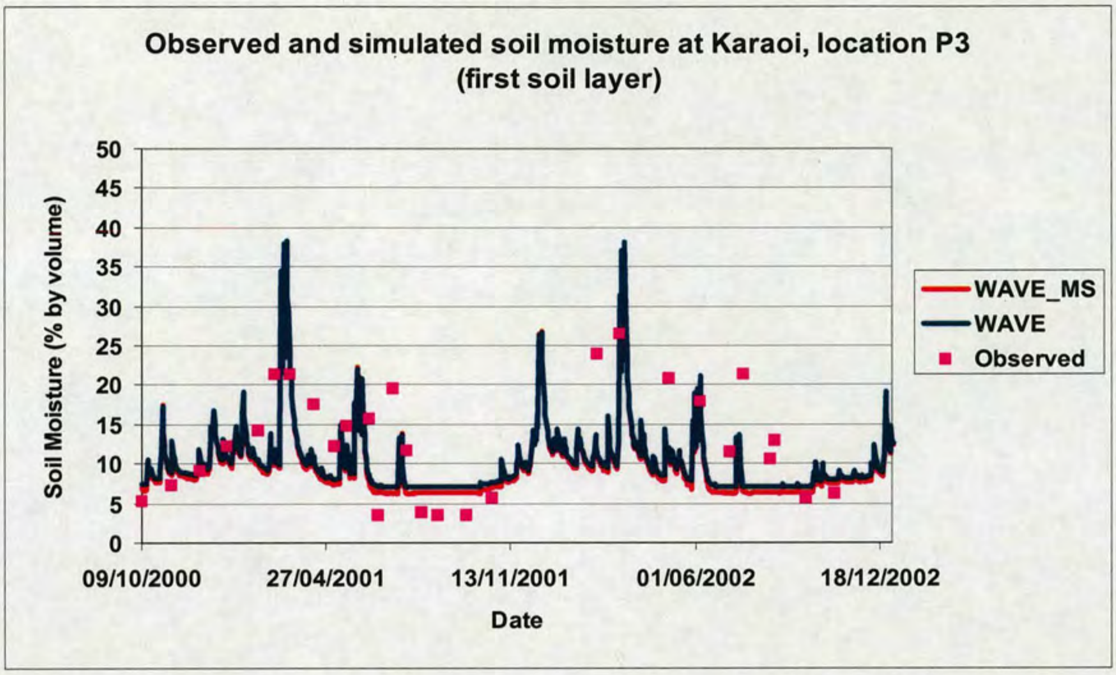


Figure 6.44: Soil moisture simulated using the WAVE and WAVE_MS models, Karaoi, location P3 (0-200 mm depth)

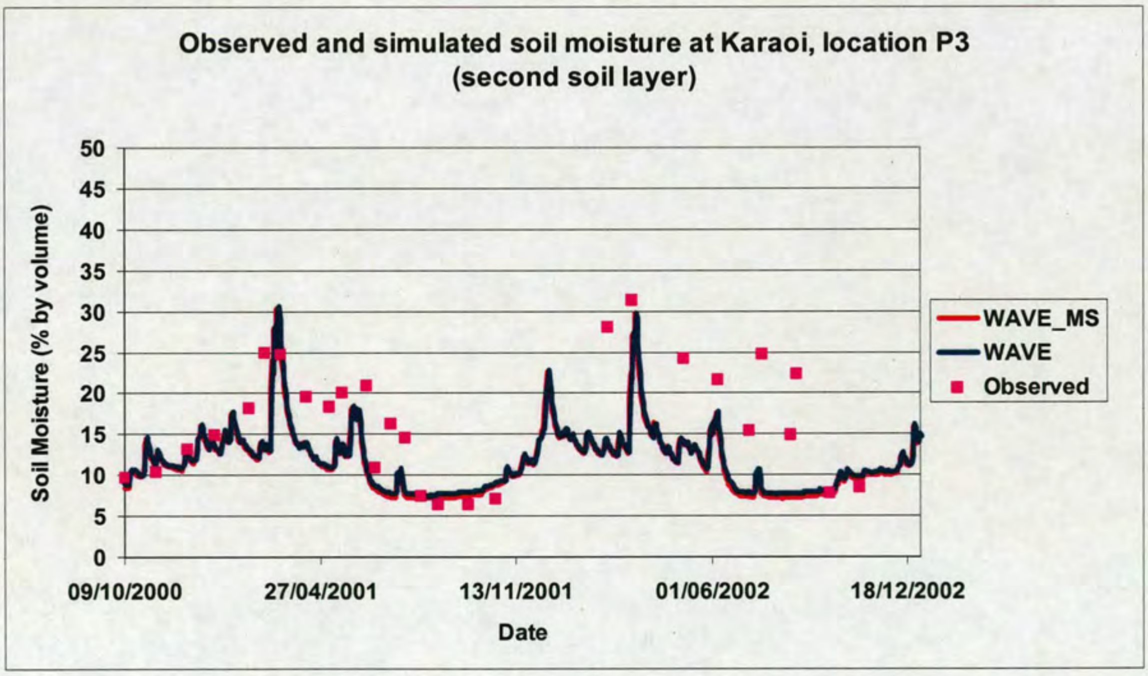


Figure 6.45: Soil moisture simulated using the WAVE and WAVE_MS models, Karaoi, location P3 (400-600 mm depth)

6.5.5 Soil Moisture Tension

Following soil moisture calibration, simulated soil moisture tension was compared with observed soil tension data where it was possible to do so. Time series of soil moisture tension data are available at different depths at Makhtali location P9, and at Karaoi location P3. The observed soil moisture tension data collected from the central site of Birlik were used in the calibration of Birlik location P3 at which there were no observed data available.

At Birlik, for all depths, there is reasonable agreement between observed and simulated soil moisture tension in terms of magnitude (Figures 6.46 and 6.47), and the results are as good as could be expected in the light of the moisture retention curves given in Figure 6.37. The effect of wetting and drying due to water application and root water uptake was not clear even in the top layer. In other words, the observed soil moisture tension data were less sensitive to irrigation application as compared with the simulated soil moisture tension. It is unfortunate that no data were available for the leaching period. No reliable tension data were available for the Birlik pilot site at locations P3 and P12. Moreover, according to the Working Paper No. 30 (Mott MacDonald, 2004), the monitoring equipment were not working efficiently particularly in Birlik due to poor drainage and waterlogging.

In Karaoi, the water table is lower than at Makhtali and Birlik, and this is clearly reflected in the relatively higher soil moisture tensions observed in the lower soil layers. The impact of two water applications on the soil moisture tension data is apparent in the upper soil layer (Figure 6.48). Perhaps the observed soil moisture tension data in this pilot area are more reliable than in other areas. The simulated data fitted the observed reasonably well. Figures 6.48 and 6.49 show that the simulated soil moisture tension matches well with the observed in the three depths under consideration, and especially in the bottom layer at a depth of 1500 mm.

In Makhtali, location P9, there has been clear influence of the second irrigation application on the observed soil moisture tension data in the upper soil layer. However, it is apparent that the first irrigation was not effective, possibly because of the amount applied was too small. The results show an under prediction of the observed soil tension values at 300 mm depth (Figure 6.50). However, the simulated soil moisture tension matches well with the observed in the other depths, especially in the bottom layer at 1500 mm depth (Figure 6.51). The under prediction of the observed soil moisture tension data at 300 mm depth shown in Figure 6.50 could be related to the chosen parameters in the soil moisture content calibration, but in view of the data problems that were known to exist, a further iteration of calibration was not carried out.

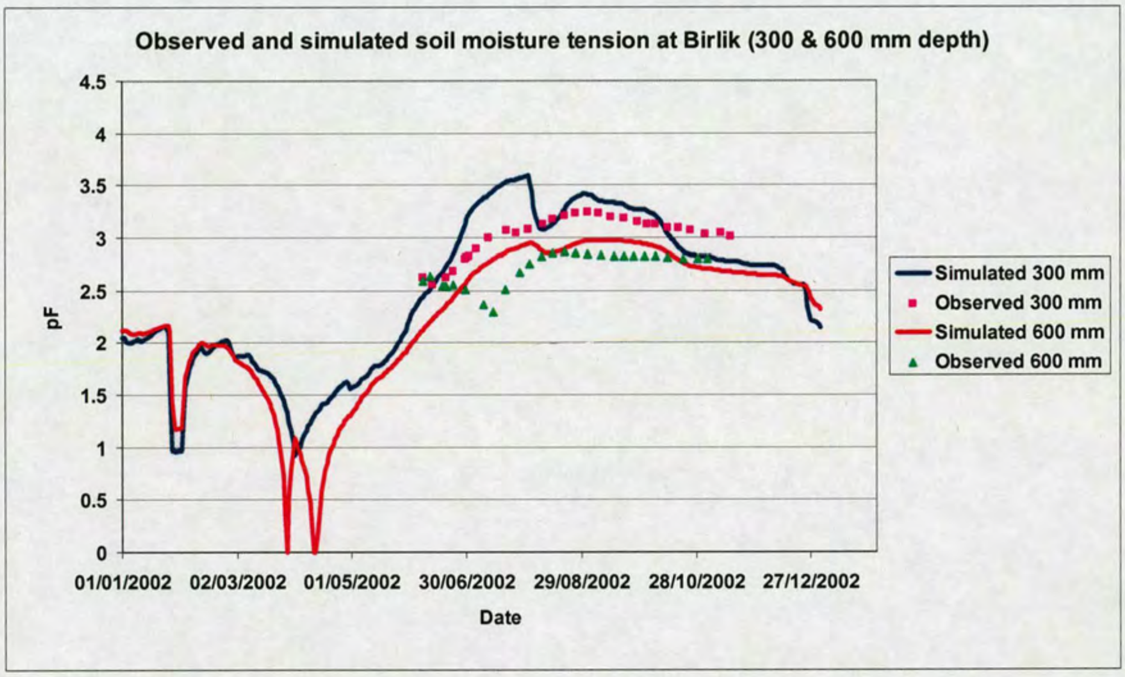


Figure 6.46: Soil moisture tension at Birlik (300 & 600 mm depth)

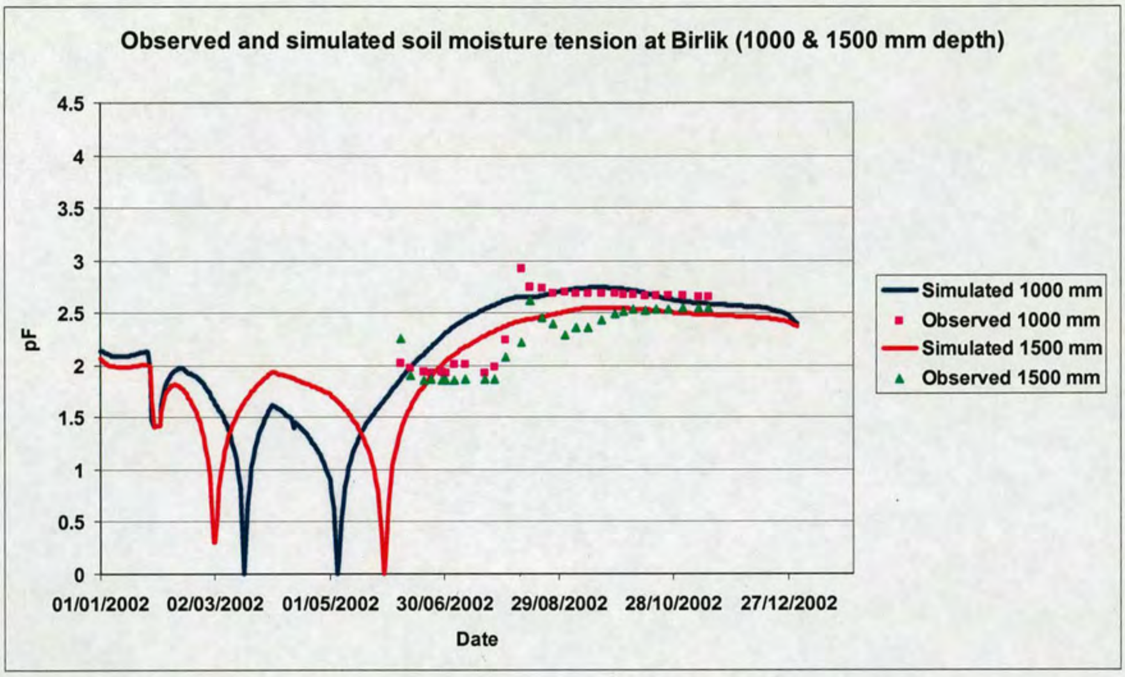


Figure 6.47: Soil moisture tension at Birlik (1000 & 1500 mm depth)

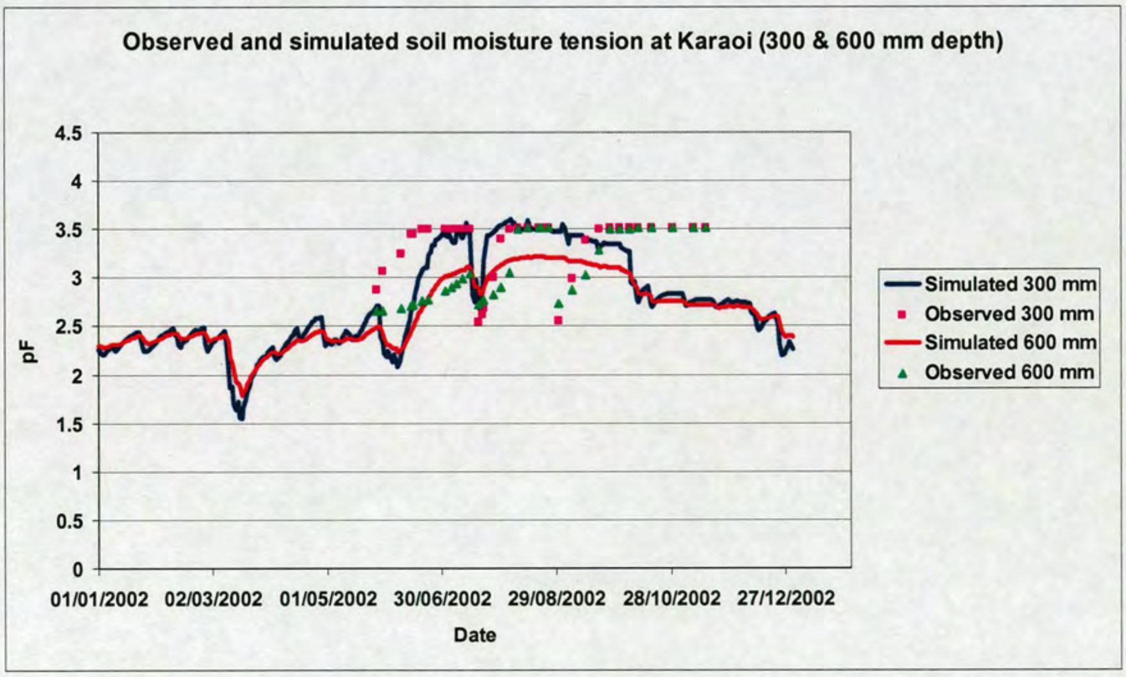


Figure 6.48: Soil moisture tension at Karaoi (300 & 600 mm depth)

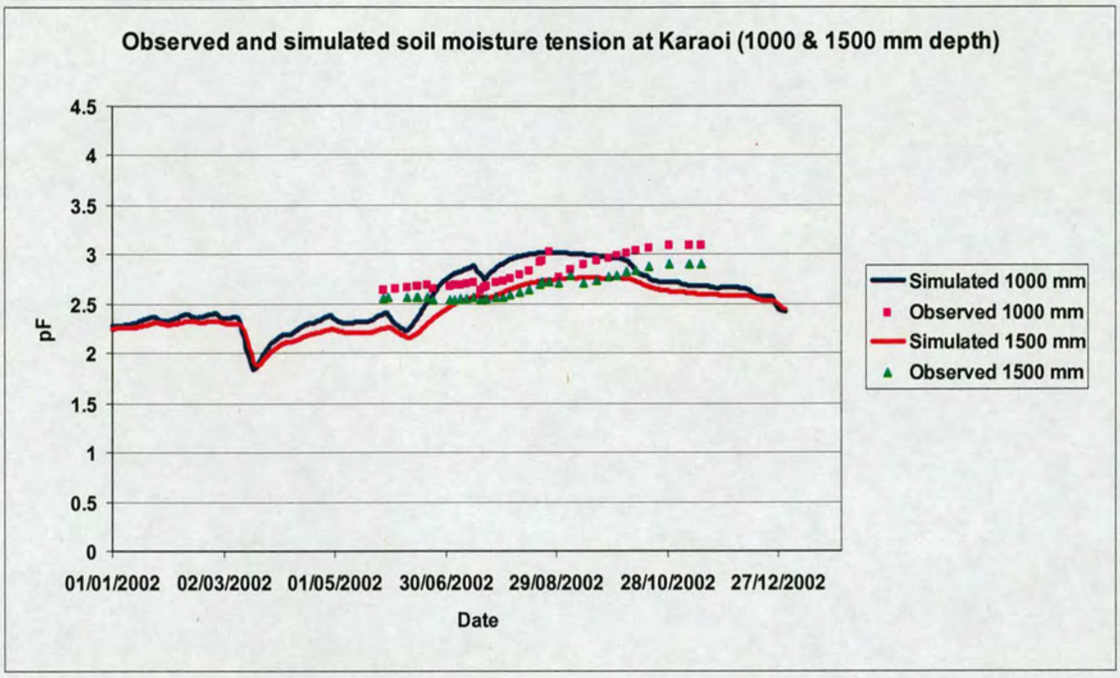


Figure 6.49: Soil moisture tension at Karaoi (1000 & 1500 mm depth)

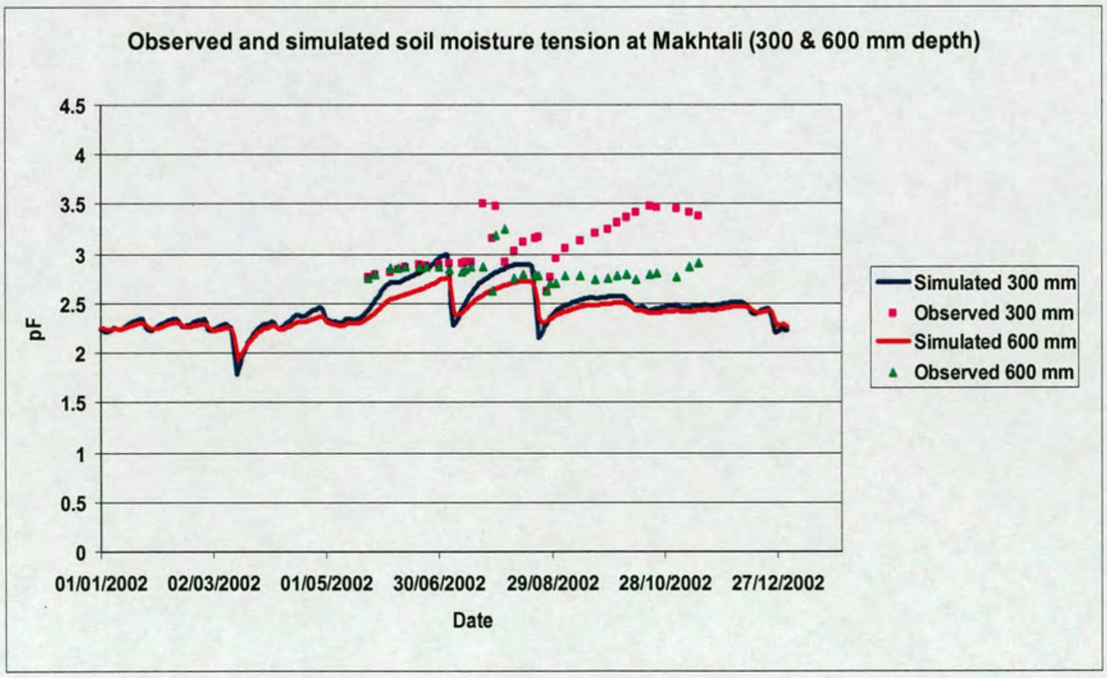


Figure 6.50: Soil moisture tension at Makhtali (300 & 600 mm depth)

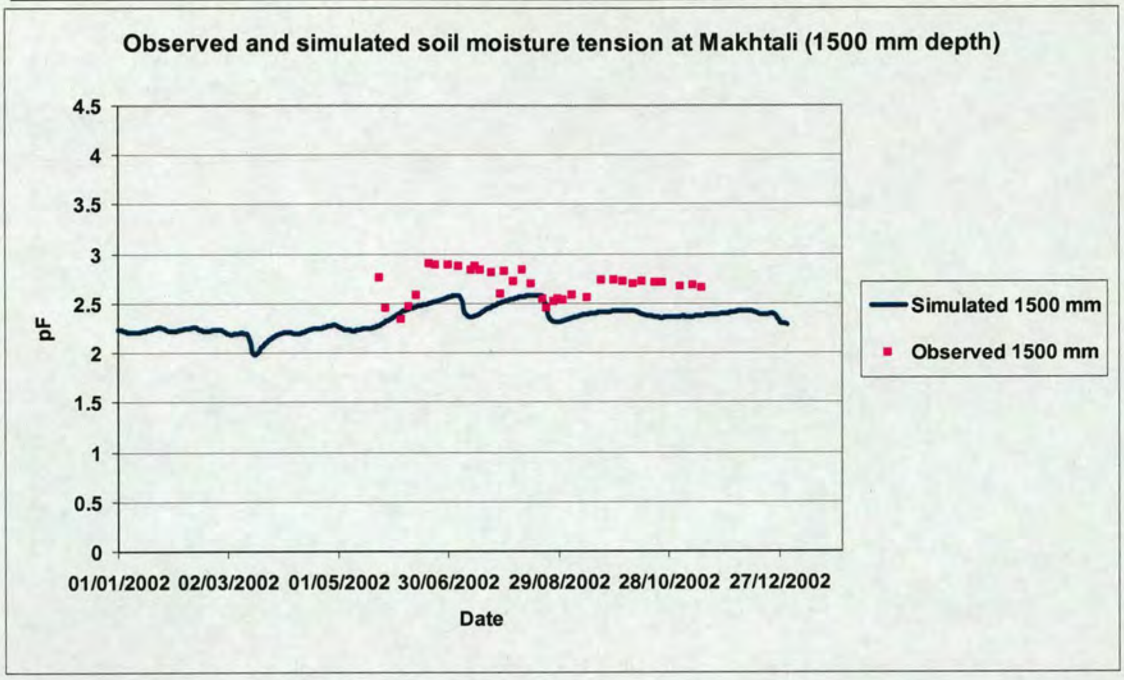


Figure 6.51: Soil moisture tension at Makhtali (1500 mm depth)

6.5.6 Soil Salinity

The soil salinity calibration was divided into two stages, in the first stage, a series of model sensitivity runs were carried out for the period 2001-2025. In these runs the sensitivity of salinity build up over the simulation period to the solute distribution constant (K_d) was tested. This parameter is required in the mobile/immobile concept. In the second stage, soil salinity calibration was carried out by running the model for two years using observed soil salinity data at different depths from the pilot areas under consideration. The objective was to match simulated and observed soil salinity by changing the distribution coefficient K_d using a trial and error process.

The sensitivity of the solute distribution constant (K_d) was tested for values of 0.5, 1.0, 2.0, 3.0, and 5.0. Figures 6.52, 6.53, and 6.54 show the influence of K_d on salinity build up, assuming Karaoi soil characteristics. This parameter has a great effect on salinity build up by controlling the mass of solutes adsorbed on the soil complex. The higher the value of K_d, the greater the mass of solutes adsorbed on the soil particles in the top three layers. As a result the simulated leaching would be less effective than with lower values of K_d. In the bottom layer (600-8000 *mm* depth), there was slight increase in soil salinity with increasing the K_d value due to the continuous accumulation of salts in this layer from the water table (Figure 6.54).

With high values of K_d lower crop yields are simulated than with low values of K_d, because a higher mass of solutes remains in the soil root zone. According to these results, it is very important to determine a value of K_d that permits reasonable salinity simulation, and reflects the observed salinity level in the project area accurately. The difficulty is that, only a few soil salinity observations are available and are insufficient to permit confident definition of K_d. A K_d value of 1.0 was chosen as being a representative value for the whole area, except for Birlik, where a value of 2.0 has been used.

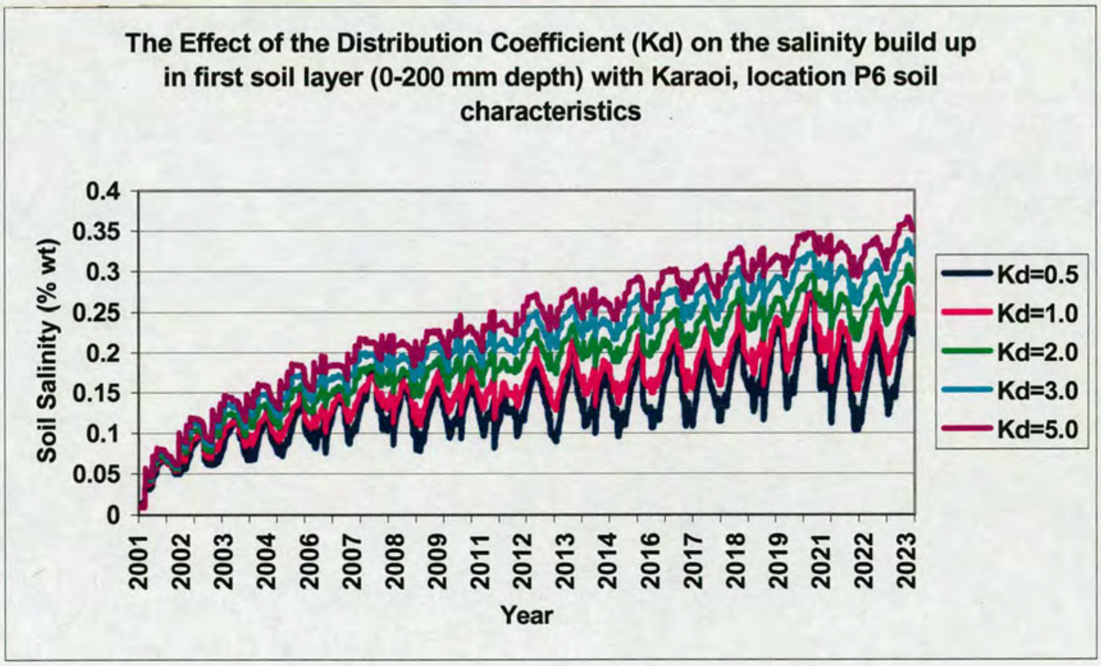


Figure 6.52: Salinity Build up at Karaoi, location P6 (0-200 mm depth)

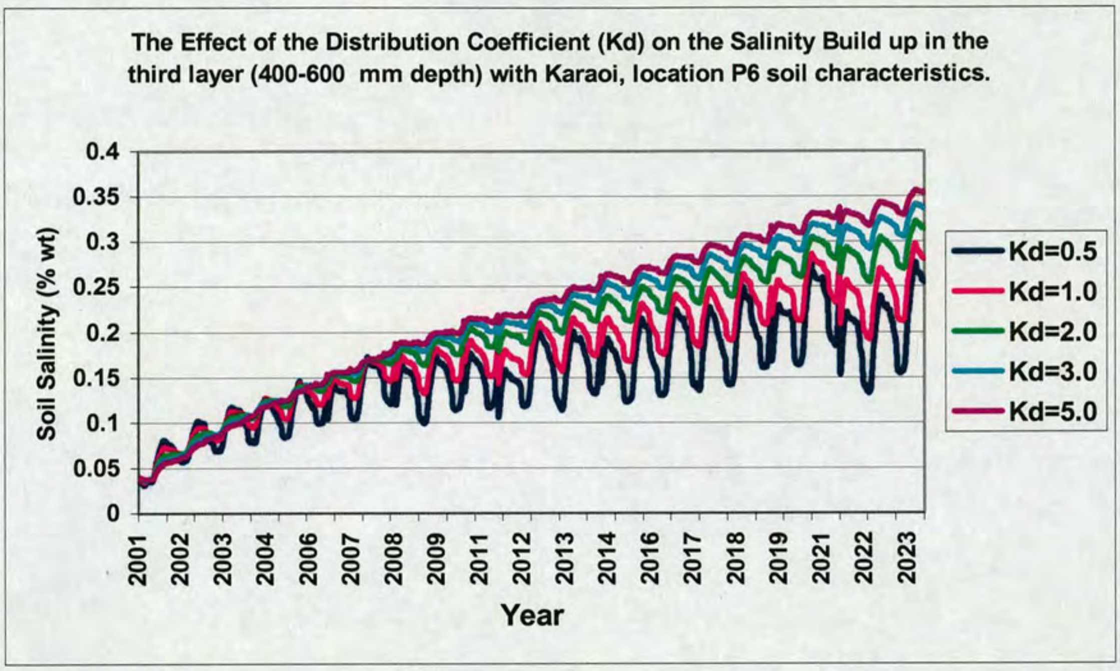


Figure 6.53: Salinity Build up at Karaoi, location P6 (400-600 mm depth)

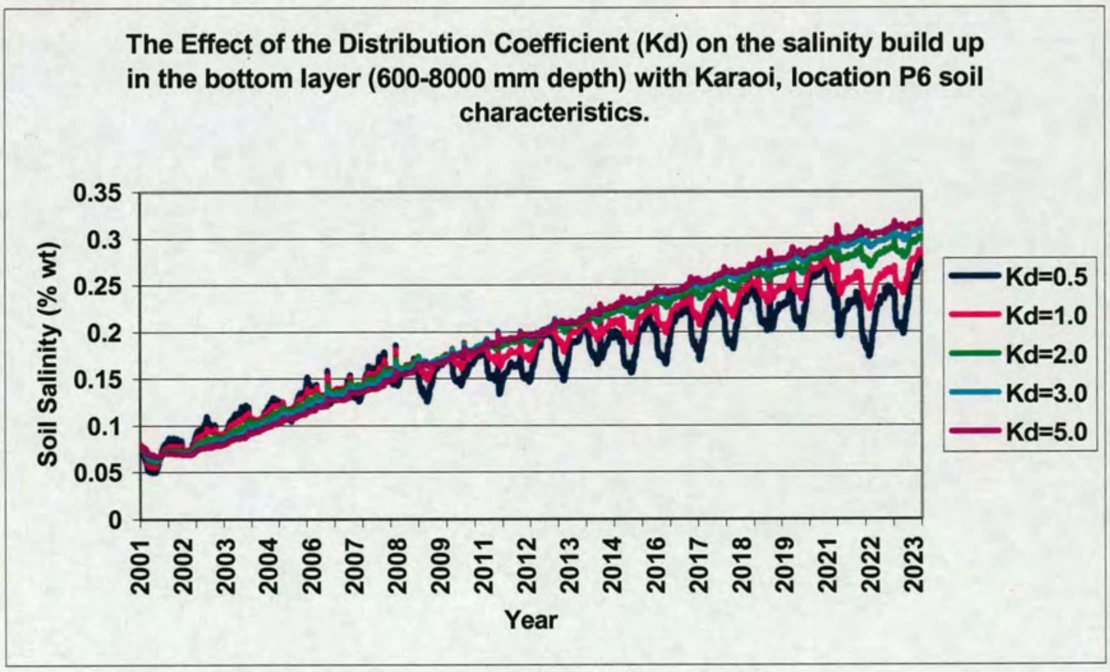


Figure 6.54: Salinity Build up at Karaoi, location P6 (600-8000 mm depth)

Establishment of efficient irrigation and drainage practice become easier if the most effective variables or parameters influencing response are identified. Another series of model sensitivity runs were carried out for the period 2001-2025. In these runs the sensitivity of irrigation and drainage management variables such as irrigation water application, irrigation water quality, leaching amount and drainage rate were tested to examine their effect on salinity build up over the simulation period. These variables are considered to be the most important factors for the establishment of efficient irrigation and drainage management practices. Sensitive variables are those that have a significant effect on salinity build up. Variables that are identified as significantly sensitive need to be treated more carefully in the construction of the scenarios required for the establishment of efficient irrigation and drainage water management. The sensitivity analysis was performed by varying each of the above mentioned variables while others were kept constant.

The sensitivity of the irrigation water application was tested in the range of 100 - 400 mm in increment of $100\,mm$ in the rate of $100\,mm$ each 30 days while leaching amount, irrigation water salinity and annual drainage were kept constant at 300 mm, 1000 mg/l and 200 mm, respectively. Figure 6.55 shows the salinity build up in the rootzone under different irrigation water applications. It is clear that, irrigation water application has a great influence on simulated salinity. Soil salinity increased by 49% as irrigation water application increased from 100 to 400 mm. The simulation results show that, with irrigation water salinity of 1000 mg/l, large irrigation application cause more salt accumulation in the rootzone even with 300 mm leaching. Irrigation water quality also has a significant impact on the salinity build up in the rootzone. The lower the quality of the irrigation water, the higher the salt loads in the rootzone (Figure 6.56). With large irrigation water applications of low quality, keeping salinity levels in the rootzone under control can only be achieved with adequate drainage rate (Figure 6.57). In other words, salinity levels in the rootzone cannot be kept constant unless the amount of salts added to the profile through irrigation water equals the amount of salts leached from the profile by drainage.

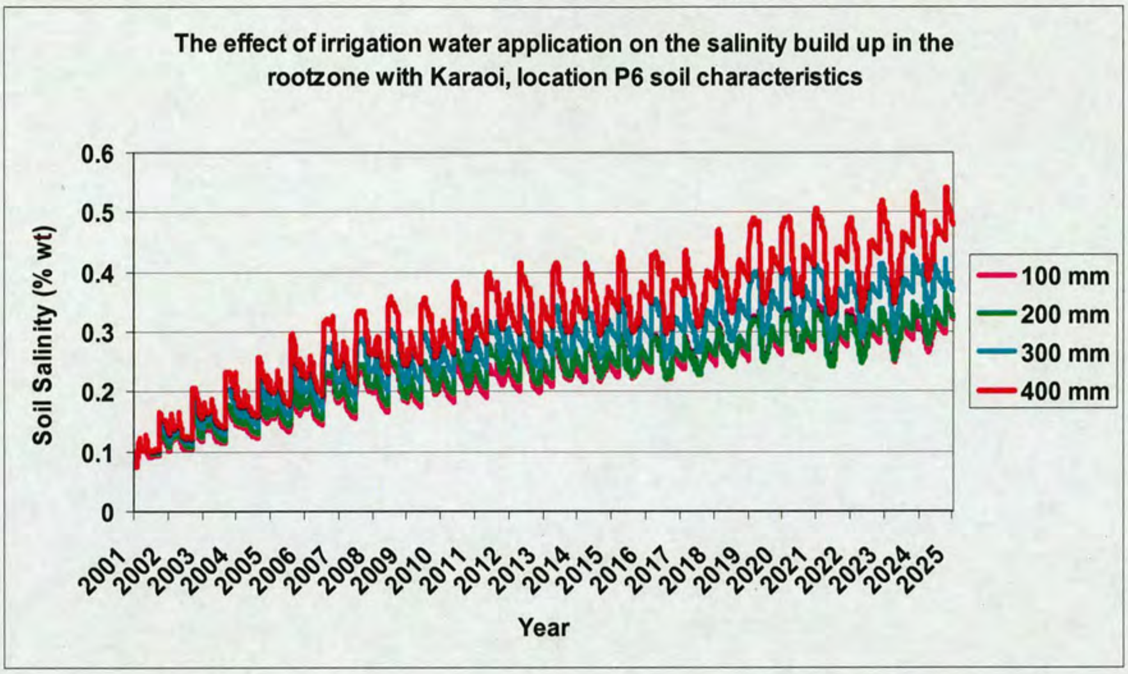


Figure 6.55: Impact of irrigation water application on the salinity build up

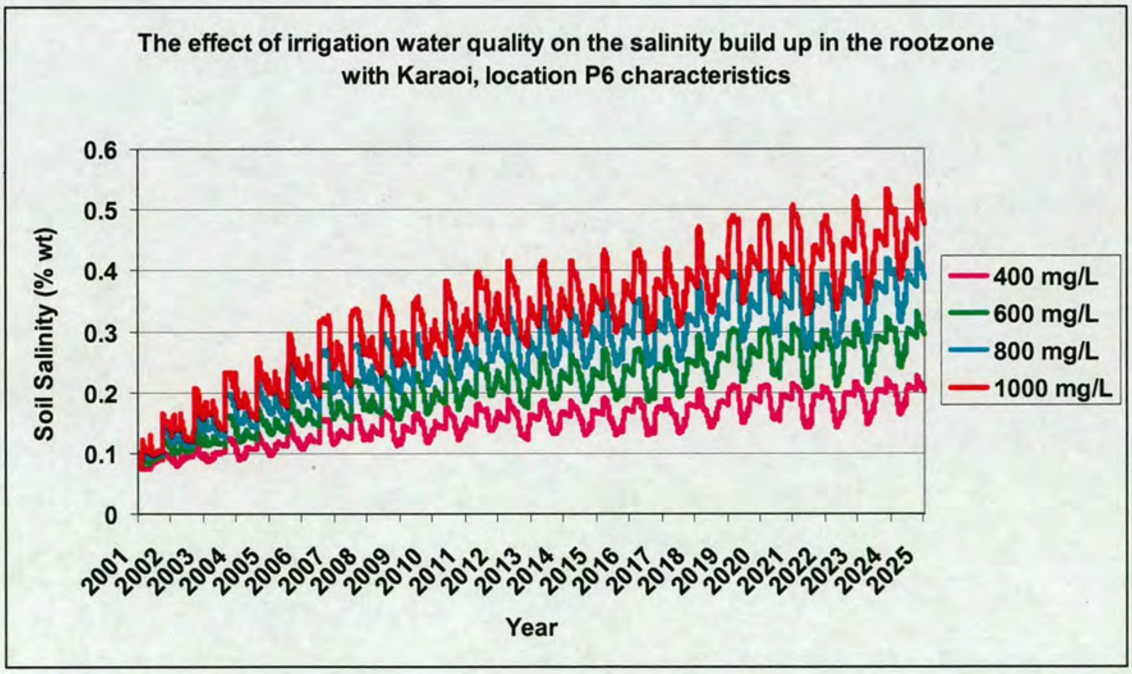


Figure 6.56: Impact of irrigation water quality on the salinity build up

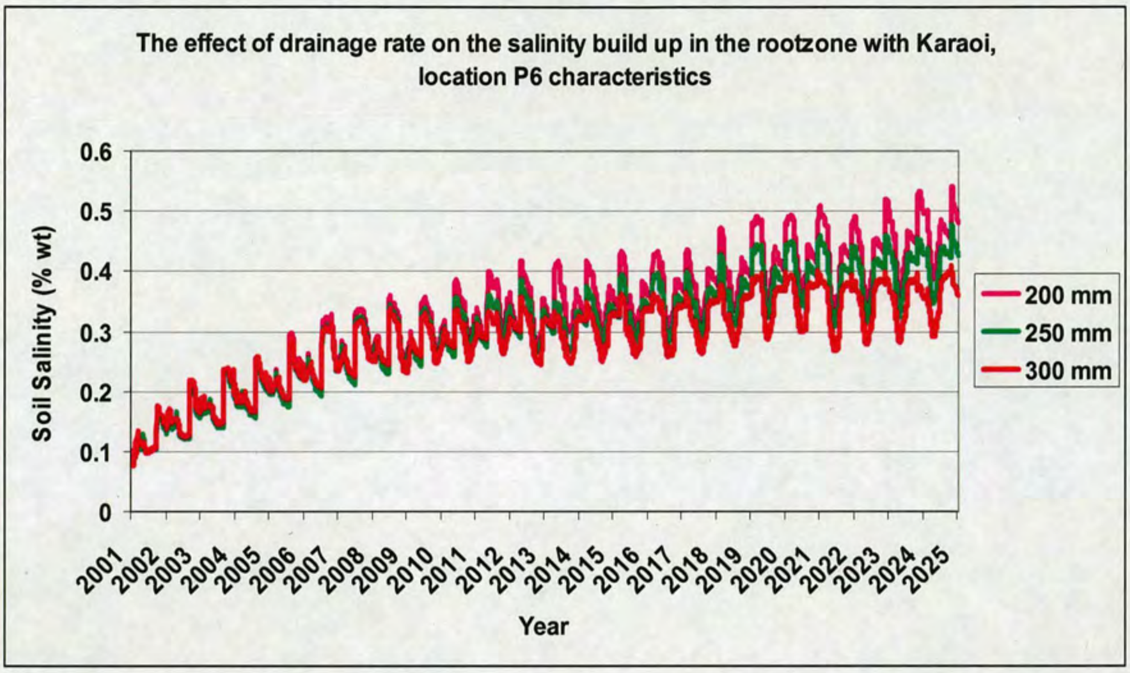


Figure 6.57: Impact of drainage rate on the salinity build up

Under low salinity conditions such as those of Karaoi, location P6, increasing the leaching amount from 100 to 300 *mm* has only a small effect on the salinity build up in the rootzone, which remains similar using 100, 200 and 300 *mm* of leaching over the simulation period (Figure 6.58). Soil salinity slightly decreases with increasing leaching. Accordingly, this variable can be ignored under such conditions. Key parameters in this case are irrigation water application and drainage rate.

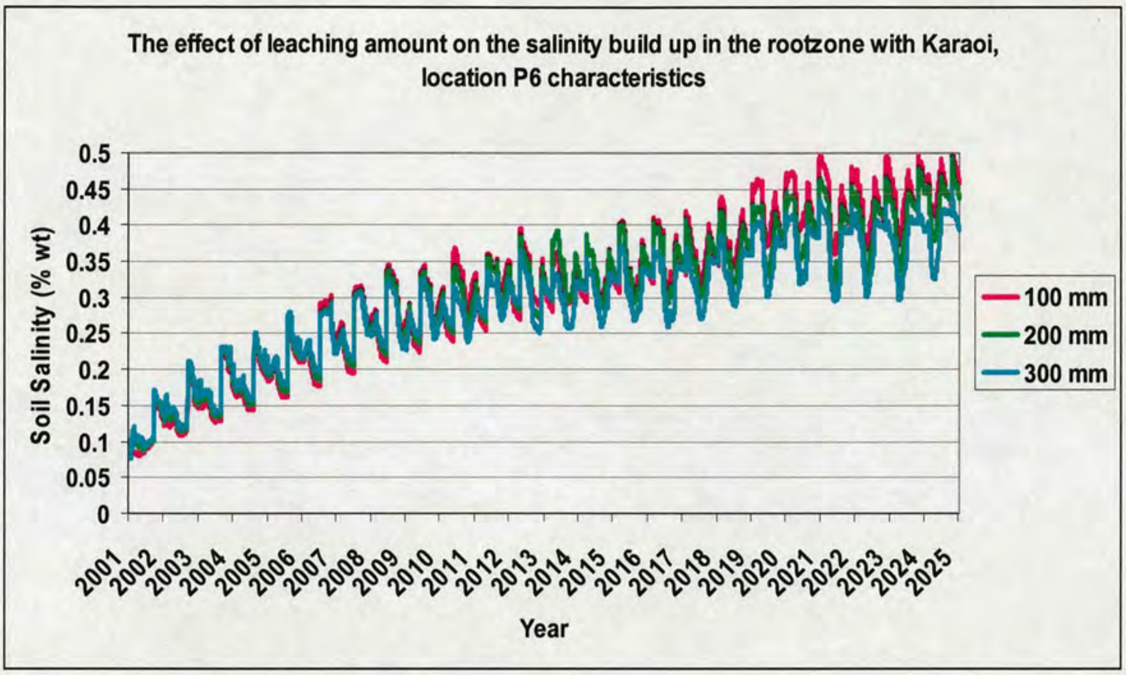


Figure 6.58: Impact of leaching amount on the salinity build up

Soil salinity is a major influence on the sustainability of irrigated agriculture in many arid and semi-arid regions. Simulating salinity build up in the WAVE and WAVE_MS models requires calibration of the distribution coefficient K_d, and to do this a high frequency of data on observed salinity are required throughout the calibration period. The fewer the samples the less well constrained is the calibration. Unfortunately, the available soil salinity data for the WRMLIP project are poor in number and quality. Because of this, great difficulty was experienced in trying to produce matches between the simulated and observed data. In the calibration processes it was not possible to reach a reasonable agreement between observed and simulated soil salinity. The restrictions in getting a good model performance in simulating soil salinity are the number and quality of the field data. The soil salinity data collected during fieldwork were very few and had some shortcomings. These shortcomings could be related to sampling errors and heterogeneity.

Figures 6.59 to 6.62 show the simulated and observed soil salinity in selected pilot areas. In addition to the graphical presentation, the high variation between observed and simulated soil salinity values is indicated by low values of R^2, EF_2 and relatively high values of CD. There are, however, few data points and while clearly the simulation of the order of magnitude of salinity is satisfactory, the data do not permit detection of increasing trends or seasonal variability. In addition, the reason for differences at some locations is thought be related to laboratory error. However, the statistics indices appear better at Karaoi, location P3 than at other sites.

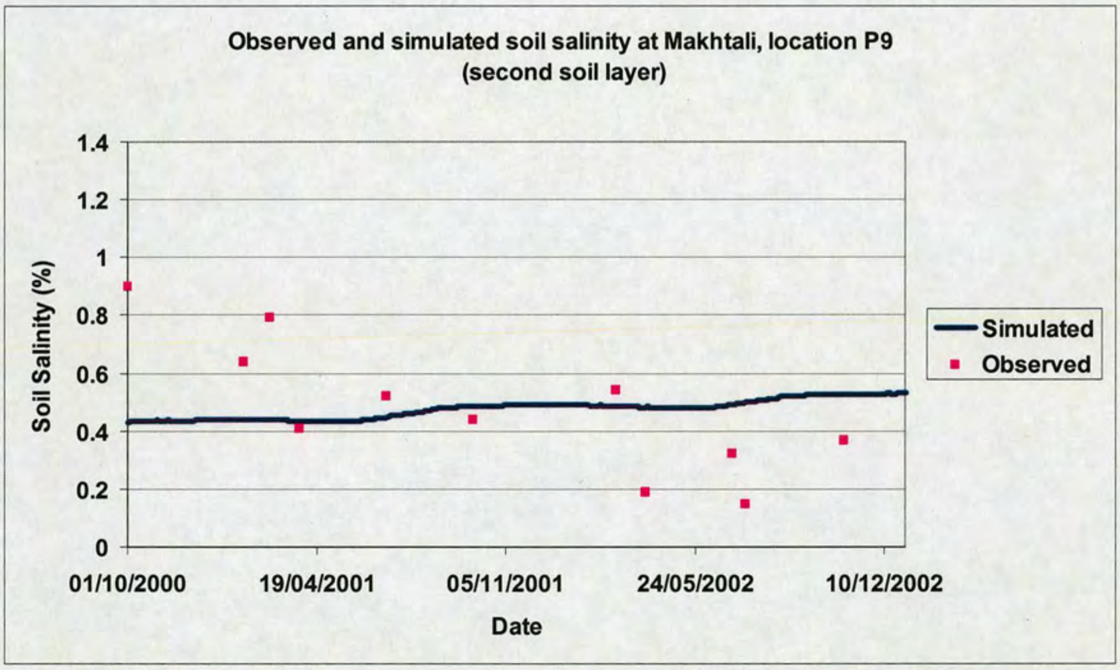


Figure 6.59: Makhtali site P9 Calibration Run – Soil salinity (200-400 mm depth)

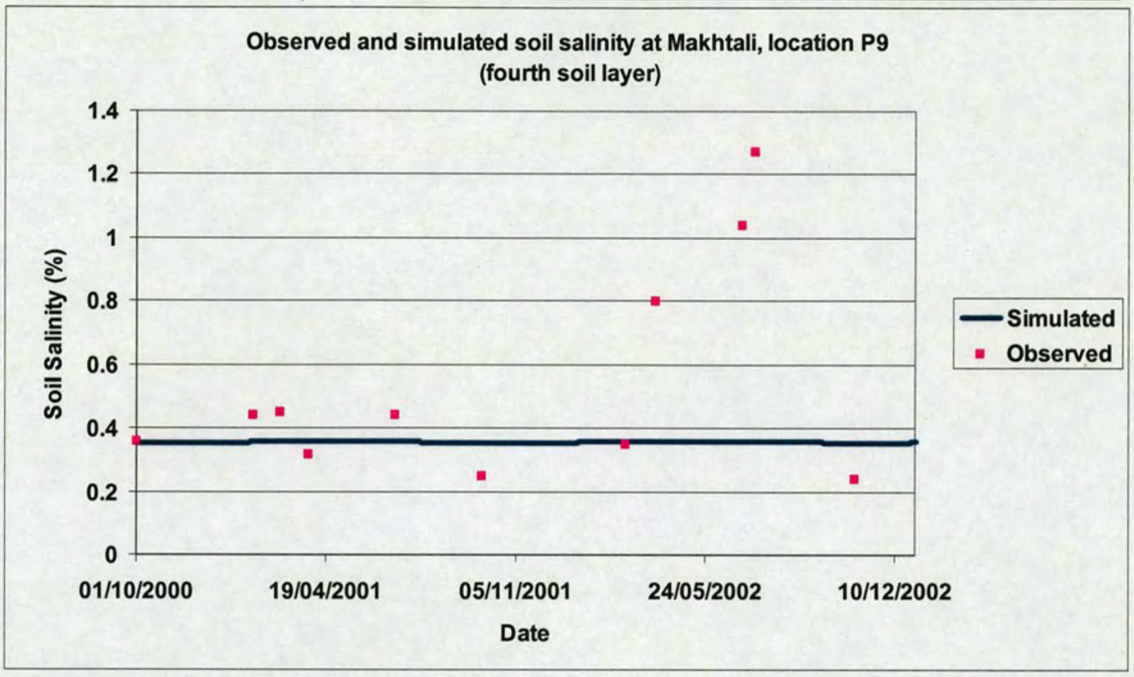


Figure 6.60: Makhtali site P9 Calibration Run – Soil Salinity (600-8000 mm depth)

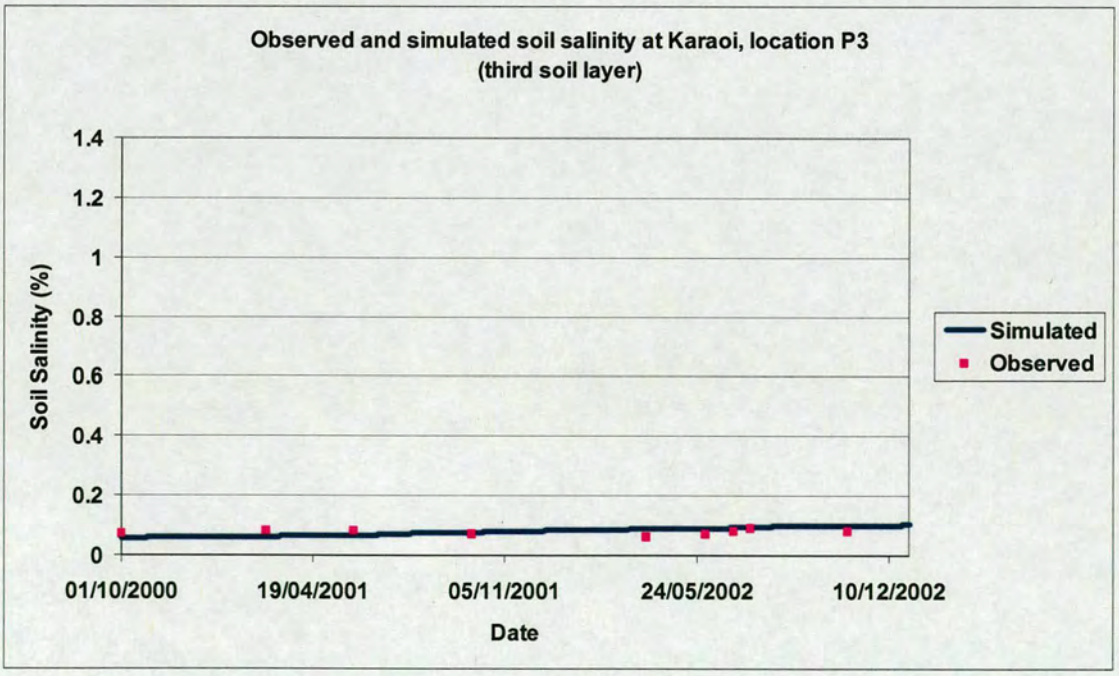


Figure 6.61: Karaoi site P3 Calibration Run – Salinity (400-600 mm depth)

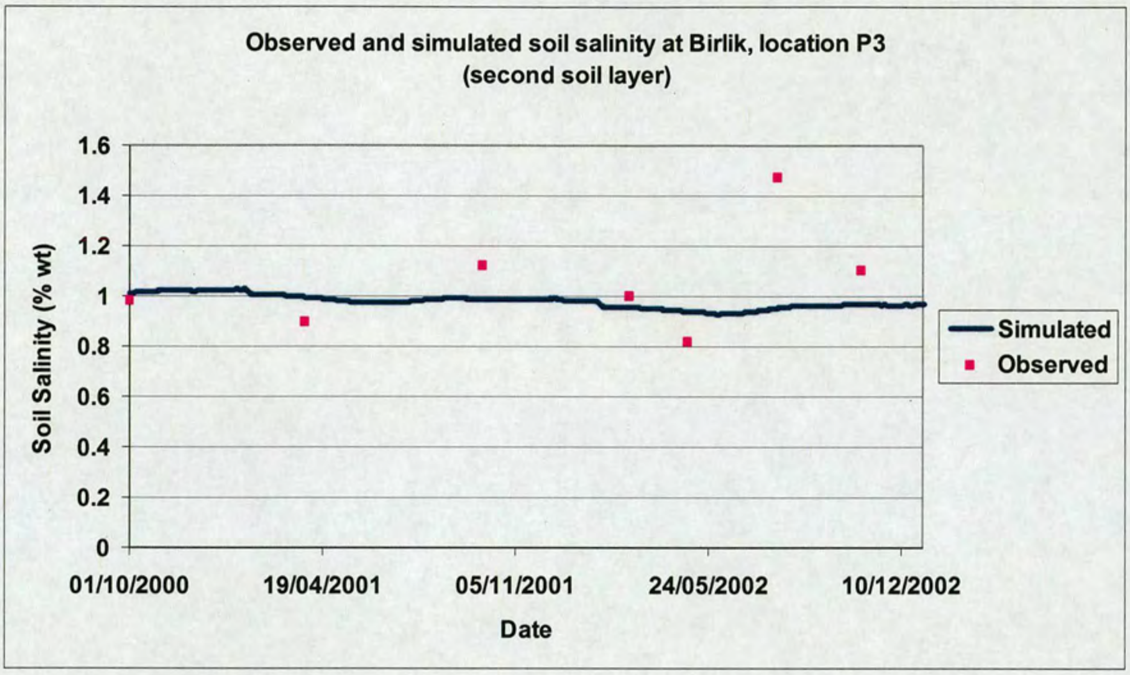


Figure 6.62: Birlik site P3 Calibration Run–Soil Salinity (200-400 mm depth)

Table 6.16: Values of the statistical parameters used in the comparison of soil salinity

Pilot Area	Layer	*MAE*	*RRMSE*	EF_2	*CD*	*CRM*	R^2
Birlik-P3	1	0.19	0.22	0.99	244.9	0.13	<0.01
	2	0.15	0.20	0.99	1083.4	0.07	0.13
	3	0.16	0.27	0.99	515.4	0.1	<0.01
	4	0.15	0.55	0.96	113.8	0.24	0.02
Birlik-P12	1	0.17	0.25	-0.01	6.57	-0.04	0.04
	2	0.17	0.26	-0.1	13.6	0.07	0.06
	3	0.11	0.16	0.11	35.2	-0.01	0.18
	4	0.26	0.93	-0.25	4.01	0.42	<0.01
Makhtali-P3	1	0.15	0.25	0.04	2.26	0.09	0.18
	2	0.16	0.25	0.05	13.2	-0.004	0.05
	3	0.2	0.3	-0.5	4.05	-0.09	0.20
	4	0.21	0.25	-0.22	2.79	0.12	0.12
Makhtali-P9	1	0.18	0.5	-0.19	10.9	0.13	0.18
	2	0.2	0.52	-0.26	36.7	0.02	0.55
	3	0.2	0.44	-0.17	6.34	0.16	0.06
	4	0.23	0.69	-0.31	3.18	0.34	0.03
Makhtali-P15	1	0.08	0.35	0.46	4.39	-0.08	0.58
	2	0.14	0.53	-0.26	1.3	-0.38	0.55
	3	0.29	0.69	-0.01	9.03	0.23	0.81
	4	0.1	0.26	-0.01	93.5	0.03	<0.01
Karaoi-P3	1	0.04	0.54	0.96	24.9	-0.43	0.99
	2	0.02	0.25	0.99	108.1	0.01	0.99
	3	0.02	0.22	0.99	170.1	-0.09	0.99
	4	0.19	1.17	0.77	14.6	0.63	0.88
Karaoi-P6	1	0.05	0.36	-0.24	3.4	-0.06	<0.01
	2	0.01	0.16	0.14	1.4	-0.11	0.64
	3	0.01	0.17	-0.01	2.4	-0.06	0.05
	4	0.01	0.15	-0.13	8	0.02	0.01

6.6 Conclusions

The modified model was set-up and calibrated using field data collected by Mott MacDonald from three pilot areas in South Kazakhstan. The data collection programme was carried out for two years from October 2000 to October 2002. The modified model is capable of dealing with the combined effect of water stress and salinity on crop transpiration and yield. In terms of soil moisture content and soil salinity, the calibration results have been satisfactory. However, soil salinity and soil moisture tension calibration was restricted by the number and quality of the data from the pilot area data collection programme. Soil salinity and soil moisture tension calibration need to be improved when more data of good quality become available. The results show poor performance in simulating soil moisture tension and soil salinity. Model calibration is limited by the number and quality of soil moisture tension and salinity data, more frequent and careful monitoring of these field data are required. The model would require re-calibration when more soil salinity data of good quality become available. An on-going field programme would permit more reliable calibration and validity of the model. The more data of good quality that can be collected the better will be model performance.

Generally, the reasonable agreement between observed and simulated soil moisture gives confidence that the WAVE_MS model can be used to predict long term water balance as well as investigating long-term salinity build up in the root zone and the effect of moisture and salinity stress on crop yield.

The calibrated model can be used in establishing irrigation and drainage management strategies that maximise crop return per unit of water applied (minimise the yield reduction due to water stress and salinity) through evaluating different irrigation and drainage management scenarios, the scenario variables are irrigation amount and time, leaching amount and drainage rate.

CHAPTER 7

Application of the WAVE Model to the Makhtaaral Region of South Kazakhstan

7.1 Introduction

This chapter describes the application of the calibrated WAVE_MS model to the Makhtaaral Region of South Kazakhstan to investigate the impacts of alternative irrigation and drainage practices on salinity and crop yield.

Following this introduction, section 7.2 demonstrates the application of the WAVE_MS model to evaluate the present irrigation and drainage practices. In Section 7.3, the procedures used for establishing efficient irrigation and drainage strategies are outlined. Evaluation of alternative irrigation and drainage practices is presented in section 7.4. Conclusions are presents in section 7.5

7.2 Evaluation of the current irrigation and drainage management practices

The modified WAVE model has been applied to evaluate current irrigation and drainage practices in the three pilot areas in the WRMLIP project area. The simulations have been driven by available historic rainfall and potential evapotranspiration data. Only 13 years of historic data were available and the historic sequence was simply repeated to provide a 25 year simulation period. This was considered to be sufficiently long to detect long-term salinity impacts.

In the simulation of the current irrigation and drainage practices, the actual irrigation time, amounts applied, and the present level of soil salinity at each location, as recorded in 2002 (Mott MacDonald, 2003a), were used as model inputs. The objective was to assess the effect of the water application, leaching amount and drainage rates on salinity build up, crop transpiration and subsequently on crop yield.

7.2.1 Crop water requirements

It is clear that since the 1990's, water supplies to the project area have been significantly lower than required for sustainable crop production. Reasonable crop yield cannot be achieved without adequate irrigation. Reductions in cotton yield in the region are attributed to inadequacy of irrigation, in addition to other factors such as soil salinity and waterlogging. Mott MacDonald (2003c) reported that soil water stress is the dominant factor effecting crop yield; the effect of salinity and water logging is significantly lower at the present time at most locations.

In all pilot areas in 2001, the total water applications (both irrigation and rainfall but excluding leaching application) were very low and could meet only 13%-17%, 20%-26% and 26% of the total crop water requirements in Birlik, Makhtali and Karaoi areas respectively. Even if the leaching amounts are considered to meet a part of the crop requirements, only 35%-47%, 32%-37% and 44% of the seasonal water requirements would have been met. Under the current conditions, crops in most locations have part of their water requirements met by root water uptake from the shallow watertable. Simulation results indicate that the amount of water supplied by the upward flux from the shallow watertable during the growing season in 2001 met 10% - 35% of the total crop water requirements, depending on location.

Figure 7.1 shows cumulative potential and simulated actual crop evapotranspiration at location P3 in the Karaoi pilot area in 2001. The simulated actual crop evapotranspiration during the growing season from mid-April to mid-October was about 473 *mm* compared with 809 *mm* potential evapotranspiration. About 35% of the total crop water requirement (60% of the actual water use) at this location was met through the upward flux from the water table. Only 67% of the potential crop yield was achieved. In terms of individual growth stages, there was a reduction in the crop water requirements by 7%, 26%, 50% and 51% for vegetative, flowering, yield formation and ripening stages respectively. This resulted in yield reductions of

2%, 12%, 25% and 33% for the same growth stages respectively. As the soil salinity in Karaoi area is still under the threshold value for salinity stress, crop transpiration simulated using original and WAVE_MS model versions was the same and the reduction in crop transpiration and yield was due to only the effect of soil water stress.

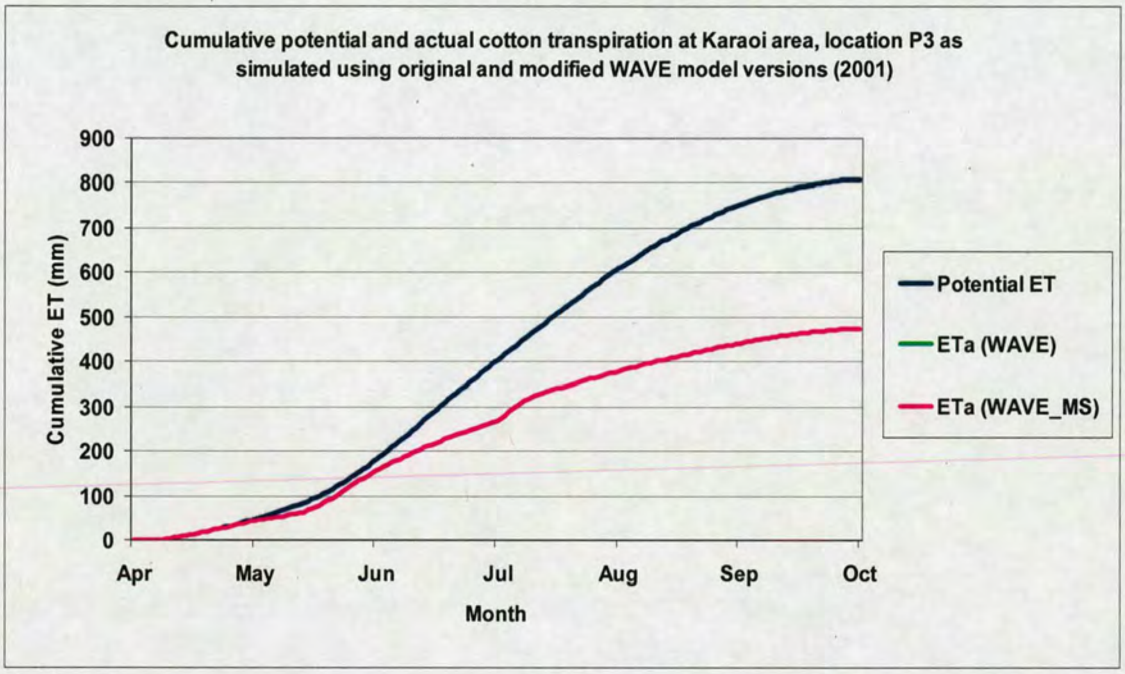


Figure 7.1: Simulated potential and actual cotton transpiration at Karaoi area, location P3.

Cotton plants in the Makhtali and Birlik areas are under the effects of both soil water stress and salinity stress. As a result, crop transpiration is lower than in Karaoi. For example, at location P9 in the Makhtali area, the simulated actual crop transpiration was about 440 *mm*; meeting only 54% of the total crop water requirements (Figure 7.2). 234 *mm* (53%) of the actual crop water use was provided by upward flux from the water table. The simulated crop yield was 54% of potential. As soil salinity in the Birlik and Makhtali areas is above the salt-tolerance threshold value, crop transpiration simulated using original WAVE model was higher than that simulated using the WAVE_MS model because the original version doesn't take into account the effect of salinity stress on transpiration.

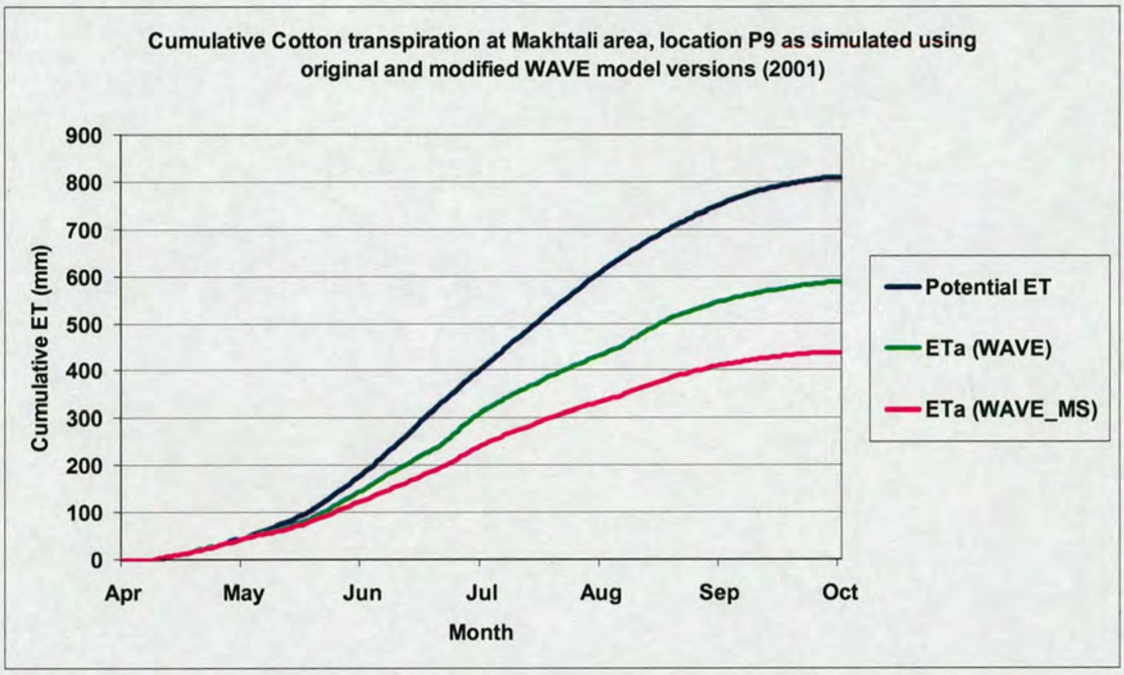


Figure 7.2: Simulated potential and actual cotton transpiration at Makhtali area, location P9.

7.2.2 Soil Salinity

According to the salinity data presented in the data collection reports (Mott MacDonald, 2003a), soil salinity in the Birlik and Makhtali areas is above the salt-tolerance threshold value of 7.7 dS/m for cotton (0.47% of dry soil weight). However, it is below threshold in the Karaoi area. The WAVE_MS model has been used to predict the soil salinity over a 25-year (notionally 2001 – 2025) simulation period. Although, water applications have been low in recent years, adequate supply would have led to a worse salinity problem than now exists in some locations in view of the poor drainage that has existed. The simulation results indicate that, rootzone salinity at Makhtali location P9 would rise by about 51% by the year 2025 (Figure 7.3) if recent irrigation and drainage practices were to continue. This would result in crop yield reduction due to salinity stress of about 44%, in addition to the reduction due to water stress. Figure 7.4 shows that soil salinity in other soil layers follows the same trend as salinity in the rootzone. The rate of salt accumulation in all layers is relatively slow. Although there was no drainage, the water table in the area falls from 4.5 m to be lower than 7.5 m over most of the simulation period as a result of the water uptake by the plant roots.

In the Birlik area, a solute distribution constant (K_d) value of 2.0 was used in the simulation, which is higher than the K_d values, used for other locations. A K_d value of 2.0 means that the leaching process is less effective than if the value was 1.0. However, root zone salinity in Birlik increased from 0.6% to only 0.71% over the simulation period to reduce the yield by about 33% in addition to the reduction due to water stress. Figure 7.5 and 7.6 show salinity build up at location P3 in the Birlik area. As a result of the higher water table in this area, salinity build up rate in the bottom soil layers is high. However, salinity build up in other layers is relatively slow. This is as a result of the continuous leaching of salts each year and the fact that salt loadings are relatively low because of inadequate irrigation. The threshold value given in the following figures is the salinity at which crop yield begins to be affected.

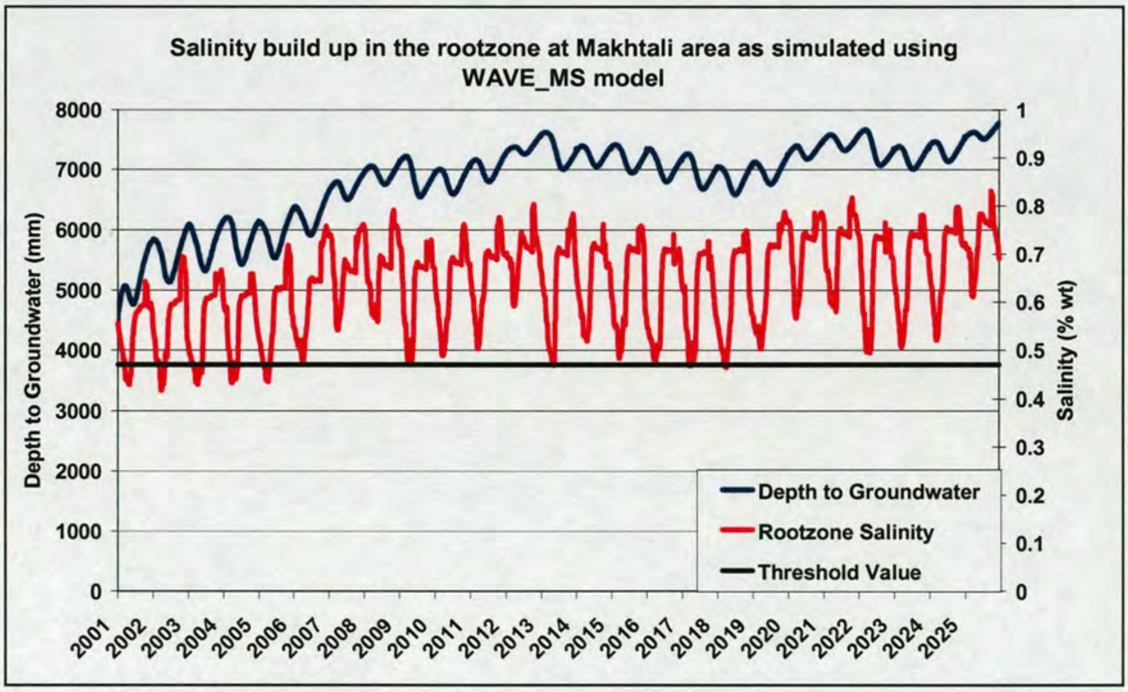


Figure 7.3: Salinity build up in the rootzone at Makhtali area, location P9

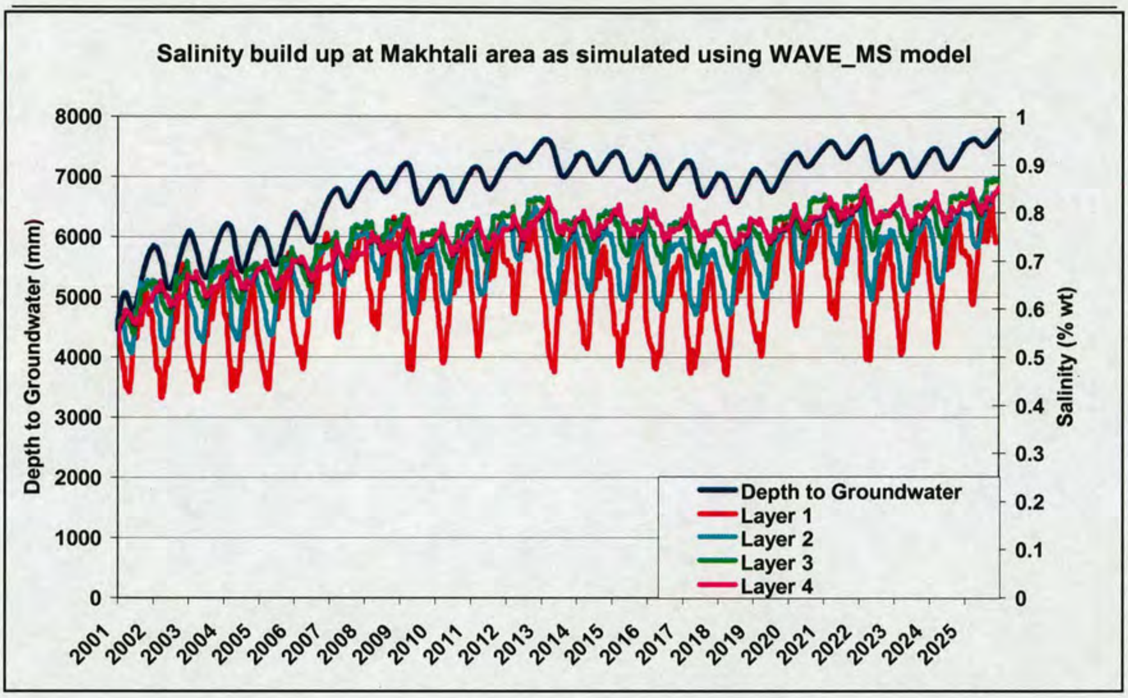


Figure 7.4: Salinity build up at Makhtali area, location P9

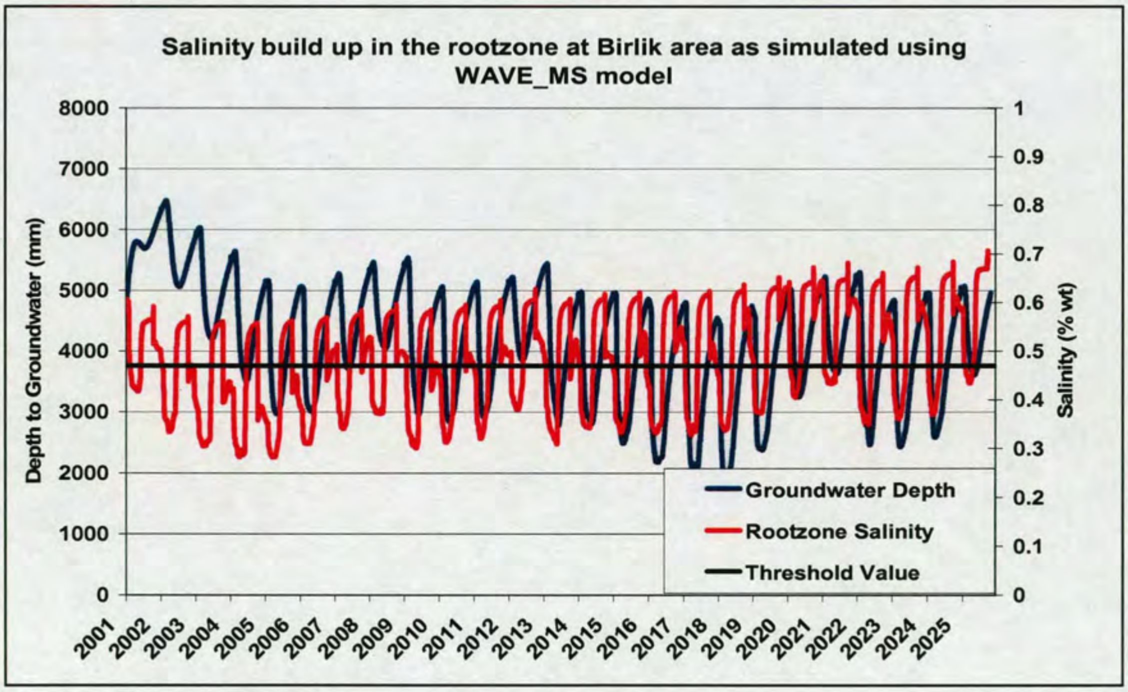


Figure 7.5: Salinity build up in the rootzone at Birlik area, location P3

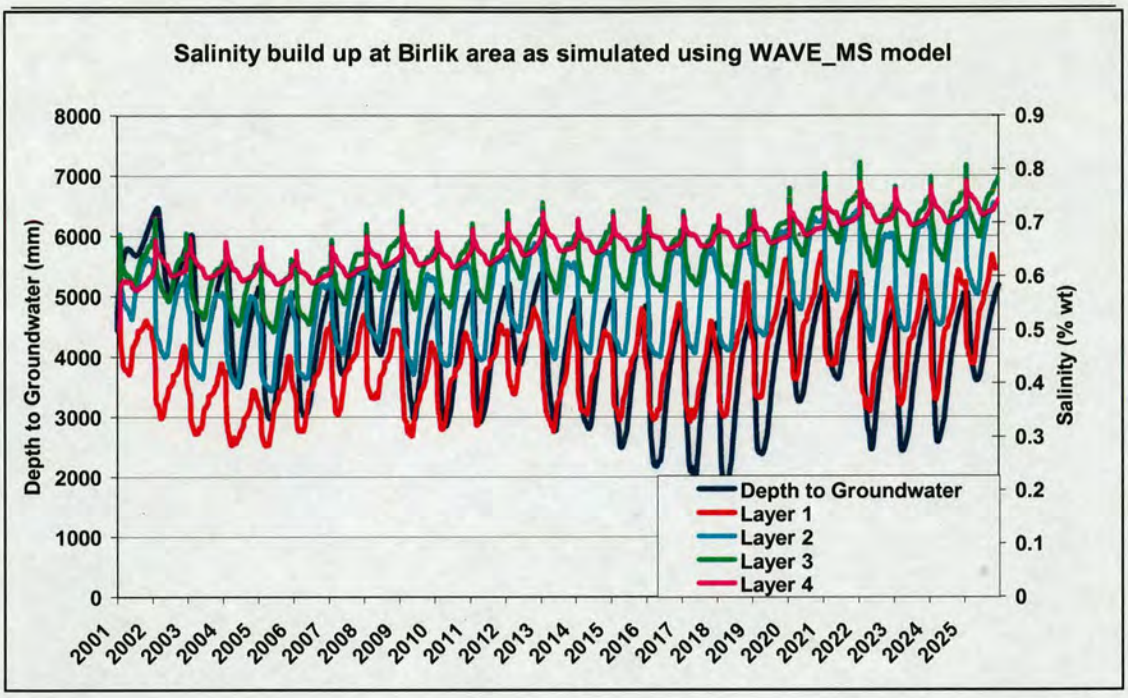


Figure 7.6: Salinity build up at Birlik area, location P3

In the Karaoi area, soil salinity remained under the critical value over the entire simulation period. The rate of salt accumulation is similar in all soil layers. The amount of salts added to the soil profile is similar to that observed at Makhtali. Over the 25 year simulation, 3.7 Kg/m^2 of salt is added to the soil profile compared with 4.0 Kg/m^2 and 3.0 Kg/m^2 added to the soil profile at Makhtali and Birlik areas respectively. Figure 7.7 and 7.8 show salinity build up in the root zone at Karaoi location P3. At Karaoi soil salinity started from a lower base, but there could eventually be a salinity problem.

As there was no salinity or waterlogging effects in the Karaoi area, the reduction in crop yield over the simulation period is related to the water stress only. The fluctuations in the depth to groundwater from one year to another are related to the variation in the seasonal rainfall and crop transpiration between years.

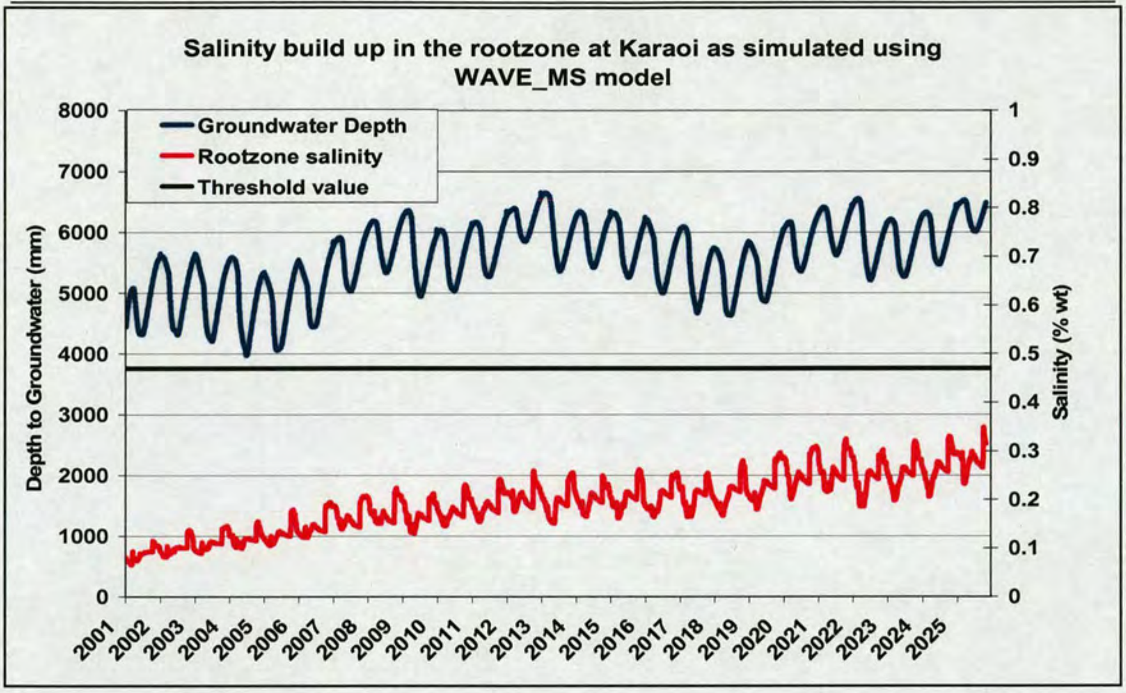


Figure 7.7: Salinity build up in the rootzone at Karaoi area, location P3

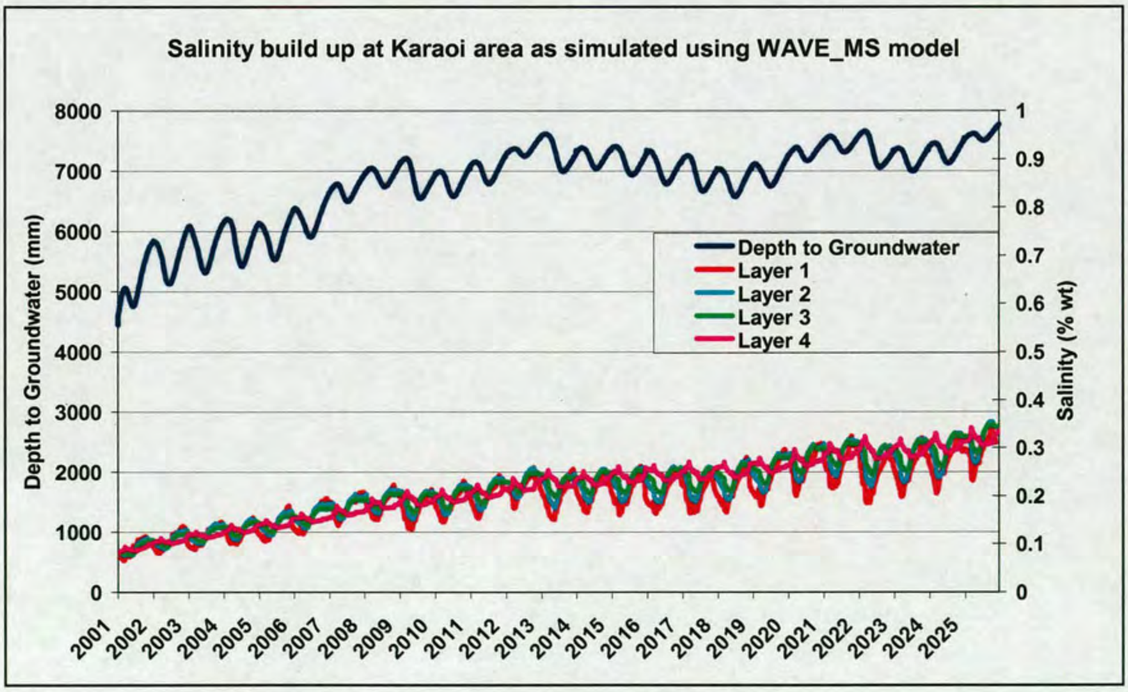


Figure 7.8: Salinity build up at Karaoi area, location P3

7.2.3 Crop yield

Long-term historical data on crop yield are not available to permit evaluation of the impact of the current irrigation and drainage management practices. The modified WAVE model has been used to assess the combined effect of water supply, soil salinity, and waterlogging on crop yield.

Two years (2001 and 2002) of observed cotton yields in the pilot areas expressed as a percent of potential maximum yield (taken as 3.9 $tonne/ha$) were compared with simulated yields using the WAVE_MS model. Results are shown in Table 7.1. There is an overestimation of the cotton yield by 14% at Makhtali and Karaoi in 2001. However, a good match with the observed yields was obtained at Birlik in both years. The model underestimates cotton yield by about 21% and 9% in Makhtali and Karaoi in 2002, respectively. The overestimation of cotton yield in Makhtali and Karaoi in 2001 can be related to factors such as plant diseases and nutrients deficiency, which caused yield reduction in addition to the effects of water stress and salinity. The model has only considered water and salinity stress. In 2002 the yield simulation at Birlik and Karaoi was reasonably good, but the very high yield reported for Makhtali was not reproduced. It is thought likely that there has been some anomaly in this data.

Table 7.1: Average observed and simulated cotton Yield in pilot areas, (%)

Pilot Area	Average Yield (%)	
	Observed	Simulated
	2001	
Makhtali	40	54
Birlik	48	46
Karaoi	053	67
	2002	
Makhtali	75	54
Birlik	53	51
Karaoi	78	69

Cotton yield was simulated using the WAVE_MS model for a period of 25 years (2001-2025) to investigate long-term water stress and salinity effects on cotton yield, assuming that recent irrigation and drainage practices continued. In the Makhtali and Birlik areas, cotton yield is under the effect of both soil salinity and soil water stress. As a result, the average reduction in crop yield was about 50% in the year 2002 in both areas. Average yield in these two areas decreased sharply from the initial values of about 54% and 45% in the first year of simulation. Figures 7.9 and 7.10 show that by the year 2025, with continuation of recent irrigation and drainage practices, 70% of the potential crop yield would be lost from the Makhtali and Birlik areas. Increasing soil salinity is the cause of continued decline in yields.

Since soil salinity in the Karaoi area remains below the threshold value for salinity stress throughout the simulation period, reduction in cotton yield is attributed to soil water stress only. The reduction in yield would remain around 30%-40% until the salinity exceeds the threshold value (Figure 7.11). At that time the reduction in yield will increase as the salinity increases. The combined effect of water stress and salinity is more harmful to crop yield than the individual effect of water stress. The slight fluctuations in crop yield from one year to another are related to variations in the seasonal rainfall between years.

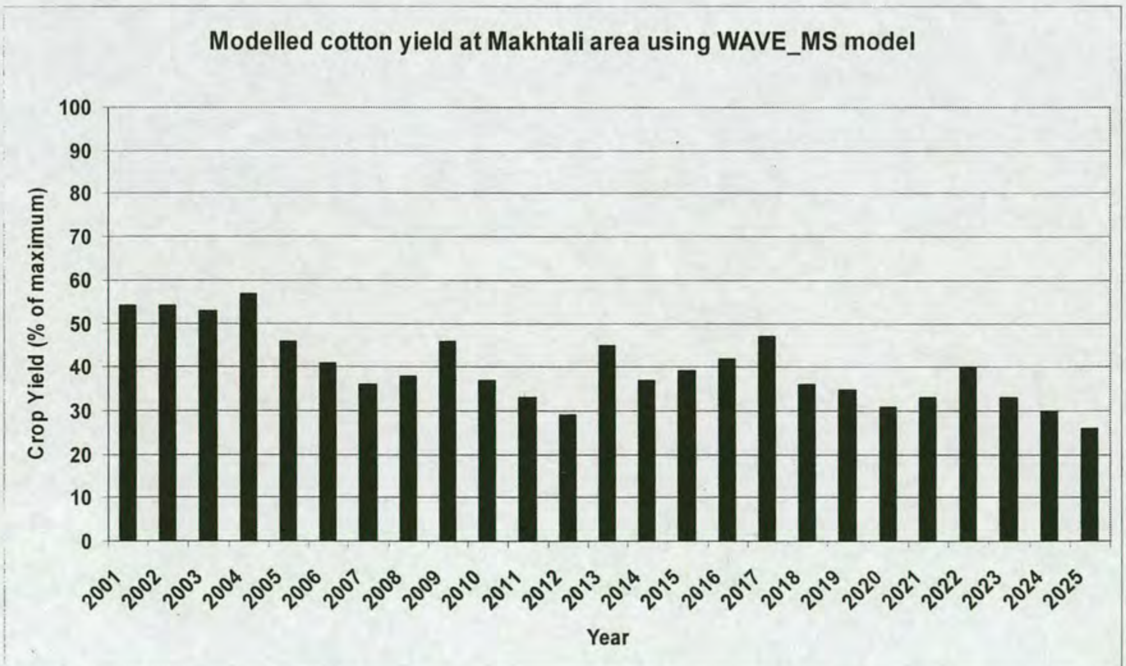


Figure 7.9: Cotton yield at Makhtali area as simulated using modified WAVE_MS model

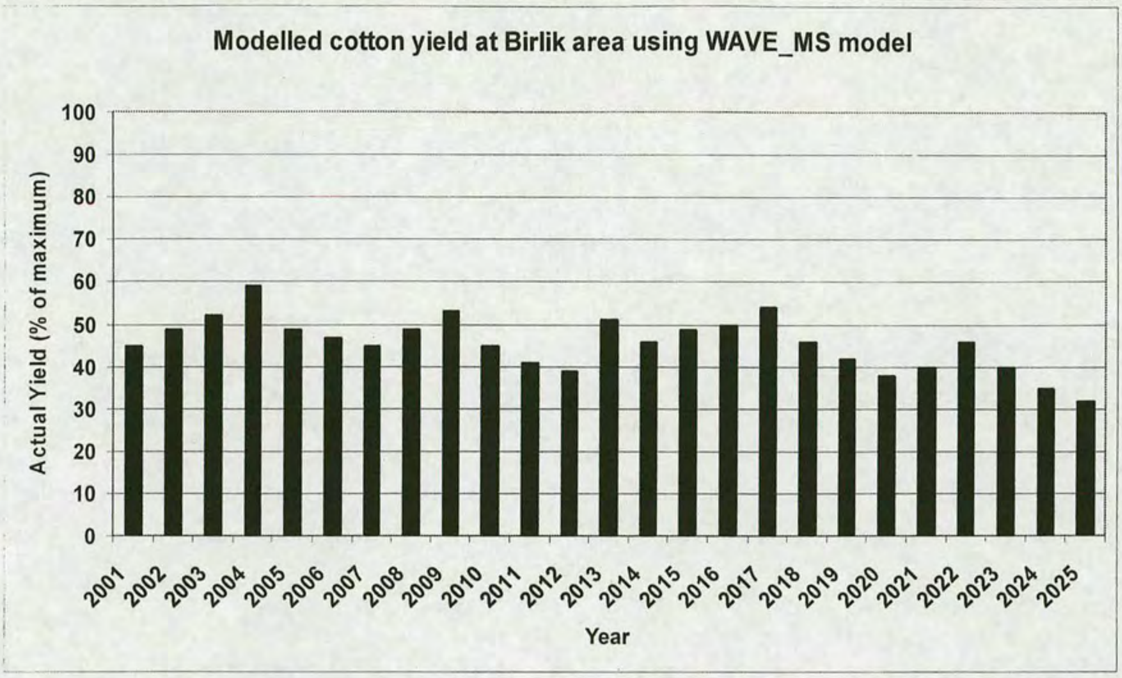


Figure 7.10: Cotton yield at Birlik area as simulated using modified WAVE_MS model

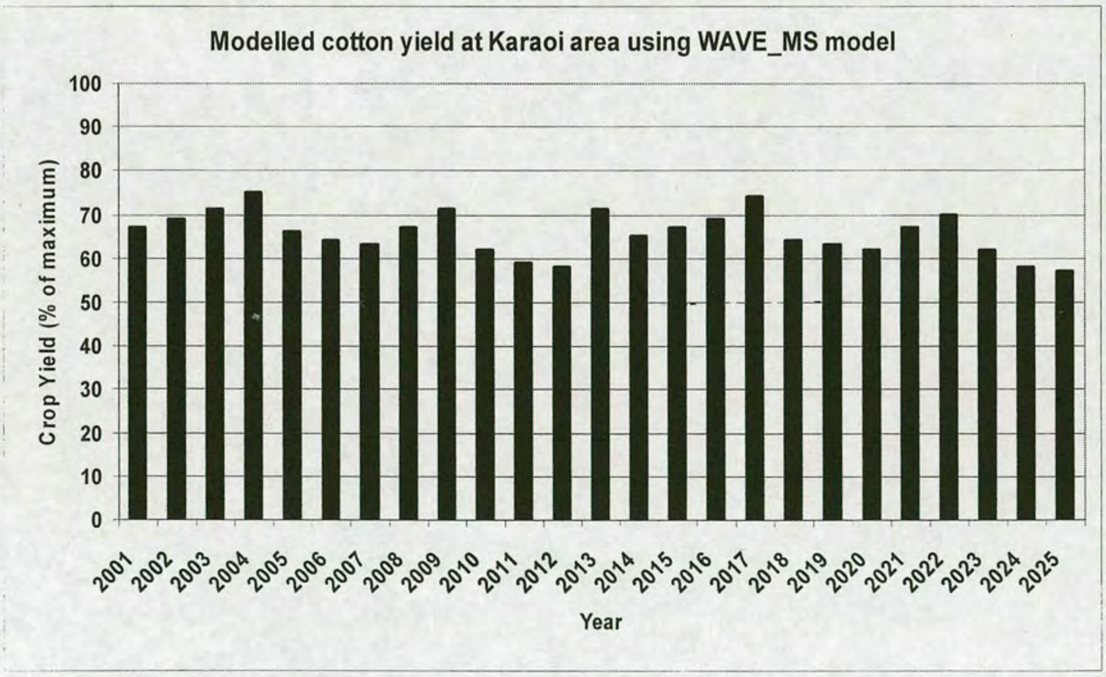


Figure 7.11: Cotton yields at Karaoi area as simulated using modified WAVE_MS model

7.3 Establishment of optimum irrigation and drainage strategies

7.3.1 Management Variables

Efficient irrigation management requires understanding of how crop yield responds to different irrigation and drainage practices. There are complex interactions between parameters, such as crop type and growth stages, irrigation application, leaching amount and drainage rate. To establish efficient irrigation and drainage strategies, the WAVE_MS model, has been used, along with the C_YIELD model to simulate the long term affects of different irrigation and drainage practices on crop yield.

Irrigation without adequate drainage results in water table rise. A shallow water table affects crop yields in different ways:- positively through its contribution by capillary flux in partially meeting crop water requirements; and negatively through its influence on salinity in the root zone, as well as through water logging. Controlling the water table position by vertical drainage is an important part of the WRMLIP project. There are of course operational costs associated with vertical drainage, and there could be trade offs between irrigation and drainage costs and yields, depending upon energy costs.

7.3.2 Costs of Irrigation and Drainage

In South Kazakhstan, farmers will pay the water authority for water supply and for associated drainage pumping. The cost of irrigation and drainage will be charged to farmers on the basis of the volume of water supplied. The cost of irrigation water supply will be 114 Tenge per 1000 m^3. The cost of drainage from a level of 20 m below ground by a VDW will be around 150 Tenge per 1000 m^3. It has been reported that about 40% of the capital cost of the project was spent on irrigation improvement and around 40 to 50% on drainage facilities (Mott MacDonald, 2000a). It is important to take these costs into account in the evaluation of the different irrigation and drainage management strategies. The objective has been to keep the irrigation and drainage costs to minimum while increasing the crop return from increased productivity of the crop. In other words, increasing the crop return by maximising the crop productivity per unit of water and unit of drainage applied. Information about other costs in addition to the cost of irrigation and drainage was not available to be included in the Cost-Benefit analysis.

As a part of the model outputs, a Cost-Benefit Index file has been created. This file indicates the relative return of each scenario, taking into account the cost of irrigation and drainage. It is based on the approximate figures taken from the WRMLIP Working Paper 14 (Mott MacDonald, 2000a). The basis of this is that the revenue from 1 hectare of cotton at maximum yield is 100,000 Tenge. The cost of water supply to farmers for irrigation and drainage is about 2000 Tenge per hectare at an overall water application depth of 10000 m^3/ha (1000 mm). Relative values have been applied as 100 for maximum yield revenue per hectare, and 2 for irrigation cost per 1000 mm applied and 2 for drainage cost per 1000 mm removed. The maximum score of the Cost-Benefit Index is 100. For each irrigation and drainage scenario, the cost index is calculated as follows:

$$CBI = 100 * Yrel\_M - (2 * Irr\_A/1000) - (2 * Drain\_A/1000) \qquad (7-1)$$

Where, CBI is the Cost-Benefit Index which is an index refers to the crop return per unit of water applied and unit of drainage;

$Yrel\_M$ is the average total relative yield over the last 10 years of simulation;

Irr_A is the amount of water applied;

$Drain\_A$ is the amount of water removed.

It is clear, even without any analysis, that the costs of irrigation and drainage will not be a significant part of the crop budget.

7.3.3 Description of scenarios

Sets of modified WAVE_MS model runs have been carried out to evaluate different irrigation and drainage scenarios over a 25-year simulation period. This period was considered to be sufficient to investigate soil water availability and salinity build up in the soil root zone under different management practices. As in the evaluation of the current irrigation and drainage practices; the runs were driven by the rainfall and evapotranspiration sequences described in section 7.2. Ten different irrigation and leaching scenarios were considered. Table 7.2 lists the scenarios considered. The amount of water applied and time of application for each scenario is given in Appendix C.

Table 7.2: Possible irrigation and leaching scenarios

Scenario	**Description**
A	400 *mm* total application, 300 *mm* leaching and 100 *mm* irrigation
B	400 *mm* total application, 200 *mm* leaching and 200 *mm* irrigation
C	600 *mm* total application, 300 *mm* leaching and 300 *mm* irrigation
D	800 *mm* total application, 400 *mm* leaching and 400 *mm* irrigation
E	800 *mm* total application, 300 *mm* leaching and 500 *mm* irrigation
F	800 *mm* total application, 200 *mm* leaching and 600 *mm* irrigation
G	1000 *mm* total application, 400 *mm* leaching and 600 *mm* irrigation
H	1000 *mm* total application, 300 *mm* leaching and 700 *mm* irrigation
I	1200 *mm* total application, 400 *mm* leaching and 800 *mm* irrigation
J	1200 *mm* total application, 300 *mm* leaching and 900 *mm* irrigation

Drainage is represented in the WAVE model as a downward flux through the bottom of the soil profile. The model provides the option to specify the required drainage rates as function of time. In other words, the actual distribution of the annual drainage required throughout the year can be varied. It can be carried out continuously over the whole year or concentrated in the winter period. In the simulations, a set of alternative drainage scenarios were used. These are presented in Table 7.3. The full set of irrigation and drainage scenarios that were considered is included in Appendix C.

Crop yield response to water stress, salinity and waterlogging was used as an indicator for evaluating the performance of the different management scenarios. The scenarios considered allow assessment of the long-term combined effect of leaching and irrigation water applications, water table position and root zone salinity on crop yield. On the basis of this evaluation, efficient irrigation and drainage strategies that lead to long-term sustainable crop yield have been identified.

Table: 7.3: Possible drainage scenarios

Scenario	Description
1	No drainage
2	100 *mm* continuous drainage at 2.274 *mm* per day
3	100 *mm* total drainage at 0.662 *mm* per day in Jan, Feb, Mar, Nov and Dec
4	200 *mm* continuous drainage at 0.548 *mm* per day
5	200 *mm* total drainage at 1.099 *mm* per day in Jan, Feb, Mar, Oct, Nov and Dec
6	200 *mm* total drainage at 1.325 *mm* per day in Jan, Feb, Mar, Nov and Dec
7	300 *mm* continuous drainage at 0.822 *mm* per day
8	300 *mm* total drainage at 1.648 *mm* per day in Jan, Feb, Mar, Oct, Nov and Dec
9	300 *mm* total drainage at 1.987 *mm* per day in Jan, Feb, Mar, Nov and Dec
10	400 *mm* continuous drainage at 1.096 *mm* per day

11	400 *mm* total drainage at 2.198 *mm* per day in Jan, Feb, Mar, Oct, Nov and Dec.
12	400 *mm* total drainage at 2.649 *mm* per day in Jan, Feb, Mar, Nov and Dec.
13	500 *mm* continuous drainage at 1.370 *mm* per day.
14	500 *mm* total drainage at 2.747 *mm* per day in Jan, Feb, Mar, Oct, Nov and Dec.
15	500 *mm* total drainage at 3.311 *mm* per day in Jan, Feb, Mar, Nov and Dec.
16	550 *mm* continuous drainage at 1.507 *mm* per day.
17	550 *mm* total drainage at 3.022 *mm* per day in Jan, Feb, Mar, Oct, Nov and Dec.
18	550 *mm* total drainage at 3.642 *mm* per day in Jan, Feb, Mar, Nov and Dec.
19	600 *mm* continuous drainage at 1.644 *mm* per day.
20	600 *mm* total drainage at 3.297 *mm* per day in Jan, Feb, Mar, Oct, Nov and Dec.
21	600 *mm* total drainage at 3.974 *mm* per day in Jan, Feb, Mar, Nov and Dec.

The possible irrigation and drainage combinations are summarized in Table 7.4. Model stability problems can occur if the simulated watertable drops below the bottom boundary of the modelled soil profile. This can happen under scenarios with low irrigation water application and high drainage. Model stability problems can also occur when the simulated watertable reaches the modelled soil surface under scenarios of high irrigation water application and low drainage. Under each of these conditions, the WAVE model crashes and fails to complete the runs being carried out. Such scenarios were considered to be infeasible.

Table 7.4: Possible irrigation and drainage combinations

Irrigation Scenarios	Annual Application (mm)	Drainage Scenarios and Annual Depth Drained (mm)																				
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
		0	100	100	200	200	200	300	300	300	400	400	400	500	500	500	550	550	550	600	600	600
A	**400**	A01	A02	A03	A04	A05	A06	A07	A08	A09	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	A21
B	**400**	B01	B02	B03	B04	B05	B06	B07	B08	B09	B10	B11	B12	B13	B14	B15	B16	B17	B18	B19	B20	B21
C	**600**	C01	C02	C03	C04	C05	C06	C07	C08	C09	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21
D	**800**	D01	D02	D03	D04	D05	D06	D07	D08	D09	D10	D11	D12	D13	D14	D15	D16	D17	D18	D19	D20	D21
E	**800**	E01	E02	E03	E04	E05	E06	E07	E08	E09	E10	E11	E12	E13	E14	E15	E16	E17	E18	E19	E20	E21
F	**800**	F01	F02	F03	F04	F05	F06	F07	F08	F09	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20	F21
G	**1000**	G01	G02	G03	G04	G05	G06	G07	G08	G09	G10	G11	G12	G13	G14	G15	G16	G17	G18	G19	G20	G21
H	**1000**	H01	H02	H03	H04	H05	H06	H07	H08	H09	H10	H11	H12	H13	H14	H15	H16	H17	H18	H19	H20	H21
I	**1200**	I01	I02	I03	I04	I05	I06	I07	I08	I09	I10	I11	I12	I13	I14	I15	I16	I17	I18	I19	I20	I21
J	**1200**	J01	J02	J03	J04	J05	J06	J07	J08	J09	J10	J11	J12	J13	J14	J15	J16	J17	J18	J19	J20	J21

7.4 Scenario Evaluation

The WAVE_MS model runs were started from the salinity values observed during the data collection programme. The 25-year runs gave valuable assessment of the cotton yield response to different irrigation and drainage combinations, and permitted identification of sustainable irrigation and drainage strategies. As the variations in soil characteristics between locations within each pilot area are small, one location in each pilot area was chosen to be representative of the area.

7.4.1 Crop Water Requirements

In the irrigation scenarios listed in Table 7.2, total water applications ranged from 100 *mm* to 1200 *mm*. Some scenarios have the same water application, but have different distributions of water application over the growing period. The objective was to examine the ability of the different irrigation scheduling scenarios to provide the soil rootzone with adequate moisture to meet a crop's transpiration requirements and to achieve acceptable and sustainable yield.

Figure 7.12 shows the effect of water stress on crop transpiration under selected irrigation and drainage scenarios averaged over the last 10 years of simulation at Karaoi. There was no soil salinity problem over the simulation period so reductions in crop transpiration and yield are attributed to soil water stress alone. It is clear that water applications under scenarios A02, C05 and D09 are inadequate to satisfy crop consumptive use. Under scenarios E06, F06, G12, H11, I19 and J19, more than 90% of the crop water requirements were met. The most suitable scenarios are those that minimise irrigation and drainage, while maintaining sustainable conditions. The indications are that water applications of 800 mm are required, accompanied by 200 mm of drainage.

In the Makhtali and Birlik areas, there is a salinity problem. Soil salinity values are above the threshold value, so that reduction in crop transpiration and yield are related to the combined effect of water stress and salinity. Figure 7.13 shows the reduction in crop transpiration at Birlik due to the combined effect of water stress and salinity under selected scenarios (averaged over the last ten years). Interestingly a water application of 800 mm, accompanied by 200 mm of drainage again produces reasonably high yields.

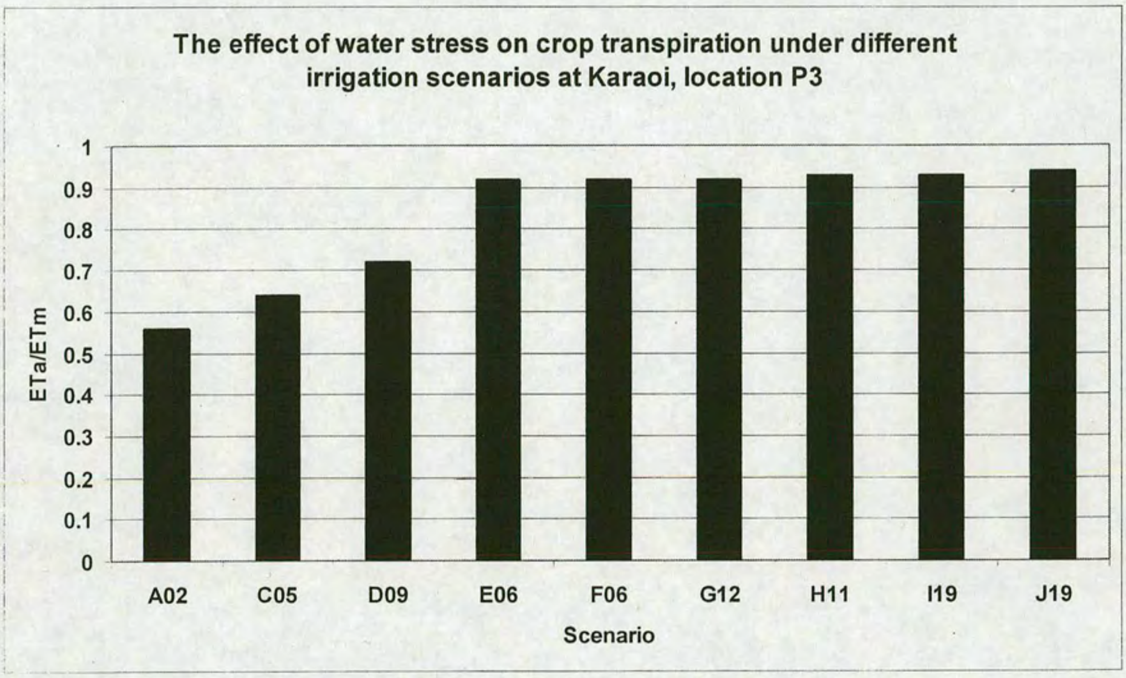


Figure 7.12: Reduction in crop transpiration under different irrigation and drainage scenarios at Karaoi area, location P3

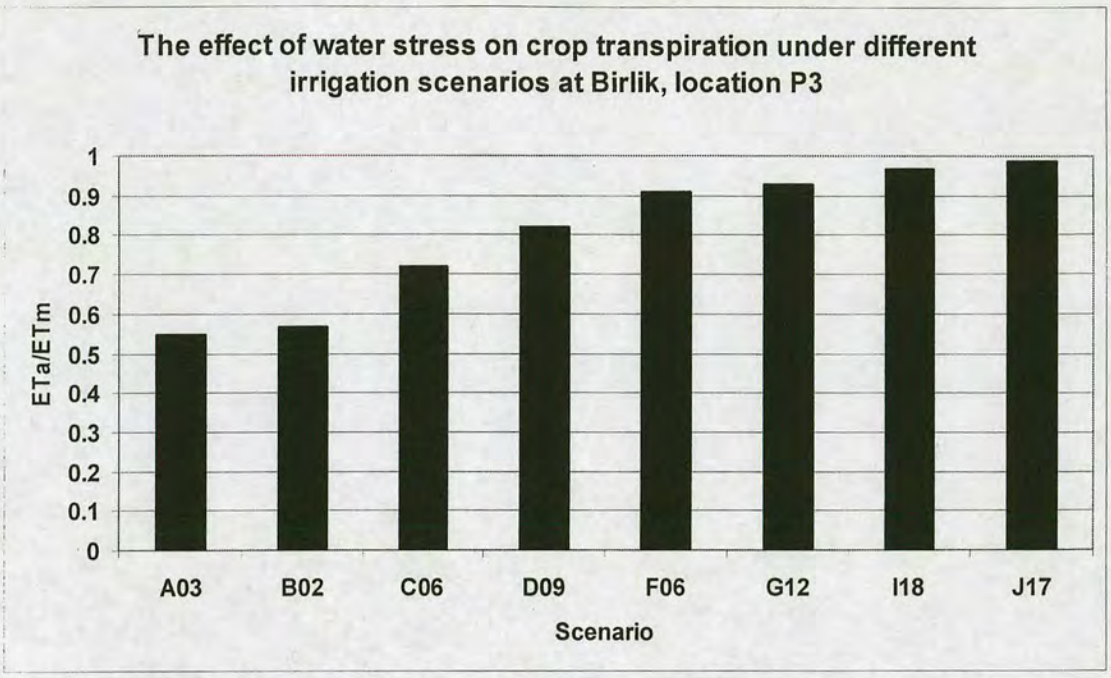


Figure 7.13: Reduction in crop transpiration under different irrigation and drainage scenarios at Birlik area, location P3

7.4.2 Salinity Build up

The reasons for salinity build up in the rootzone since the early 1990s were insufficient leaching applications and inadequate drainage. For the Karaoi area, where there was no salinity problem at the start of simulation. The rate of salinity build up in the rootzone over the simulation period was more rapid than in the other pilot areas for most scenarios.

With leaching amounts of 300 – 400 mm, the rate of salt accumulation in the rootzone depends mainly on the drainage rate. The higher the drainage rate, the lower the salt accumulations in the soil profile. Figure 7.14 shows salinity build up in the rootzone at Karaoi under scenarios of low drainage. Under the conditions of this scenario, salinity increases significantly due to low drainage rates, but remained below the salt-tolerance threshold value over the simulation period. Only 57% of maximum yield can be achieved, however because of water stress. The simulation results indicate that to achieve acceptable crop yields, and to maintain rootzone salinity within acceptable limits in the long-term, leaching application of 300 – 400 *mm* accompanied by 900 mm or irrigation and 600 *mm* of drainage is requried (Figure 7.15). This produces a sustainable relative crop yield of 93%. Drainage of less than 600 *mm* may cause watertable rise, which in turn will contribute to salinity build up in the rootzone. Figure 7.16 shows a scenario with lowere irrigation and drainage. With lower drainage, the water table rises significantly. Less irrigation is required as the water table will contribute to crop consumptive use, but the rootzone salinity continues to rise, and there is no indication that it is stabilising as in Figure 7.15.

In the Makhtali area, rootzone soil salinity was above the salt-tolerance threshold at the start of simulation. Even under low irrigation applications and low drainage rates, soil salinity can be controlled, but not below the threshold value for salinity stress. This is demonstrated in Figure 7.17. Salinity fluctuates within the same band throughout the simulation and there is no trend of increasing salinity. The reason for this is that the water table is relatively deep and the amount of salts added to the profile through irrigation in balance with the amount of salts removed from the profile by leaching and drainage. Under the conditions of this scenario, the plant is under salinity stress over the simulation period, but the salinity stress is not severe and reduces crop yield by only 9%. There is a further 41% of yield reduction caused by water stress. It is of interest to note that with moderate drainage, salinity can be controlled, but the yield reduction due to water stress is unlikely to be acceptable. To improve yield requires more irrigation, which in turn requires more drainage. On a long-term basis, rootzone soil salinity can be maintained below the salt-tolerance threshold with adequate annual drainage (400 *mm*) coupled with appropriate leaching applications (400 *mm*), and 600 mm of irrigation. This scenario produces 90% of maximum yield. Figure 7.18 shows a sustainable scenario that maintains rootzone salinity below the salt-tolerance threshold. The highest sustainable crop yield of 98% can be achieved with water applications of 1200 *mm* coupled with high drainage rate of 550 *mm* continuous at 1.507 *mm* per day (scenario J16). This is demonstrated in Figure 7.19.

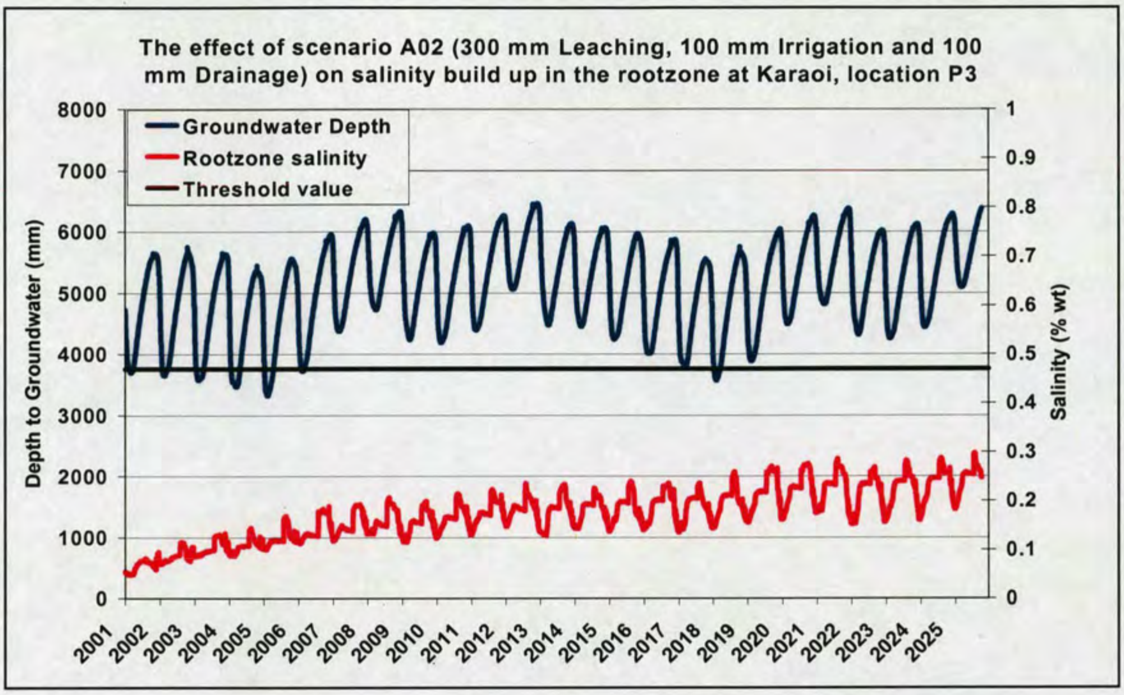


Figure 7.14: Salinity build up in the rootzone under scenario of low drainage at Karaoi area, location P3

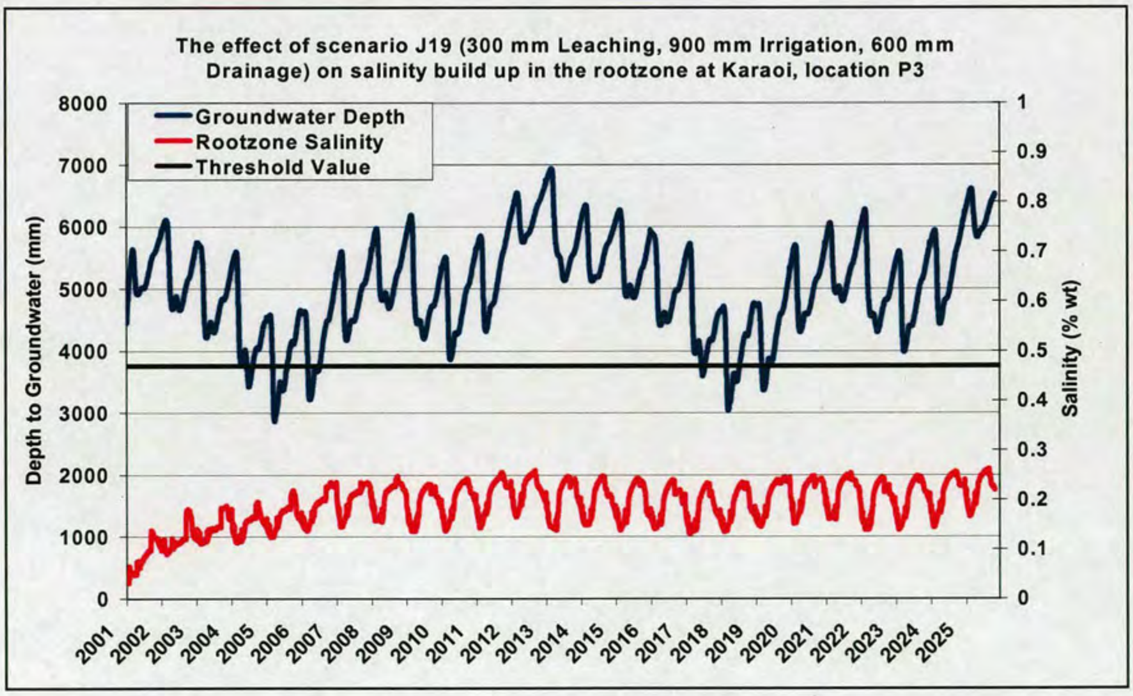


Figure 7.15: Salinity build up in the rootzone under scenario of high drainage at Karaoi area, location P3

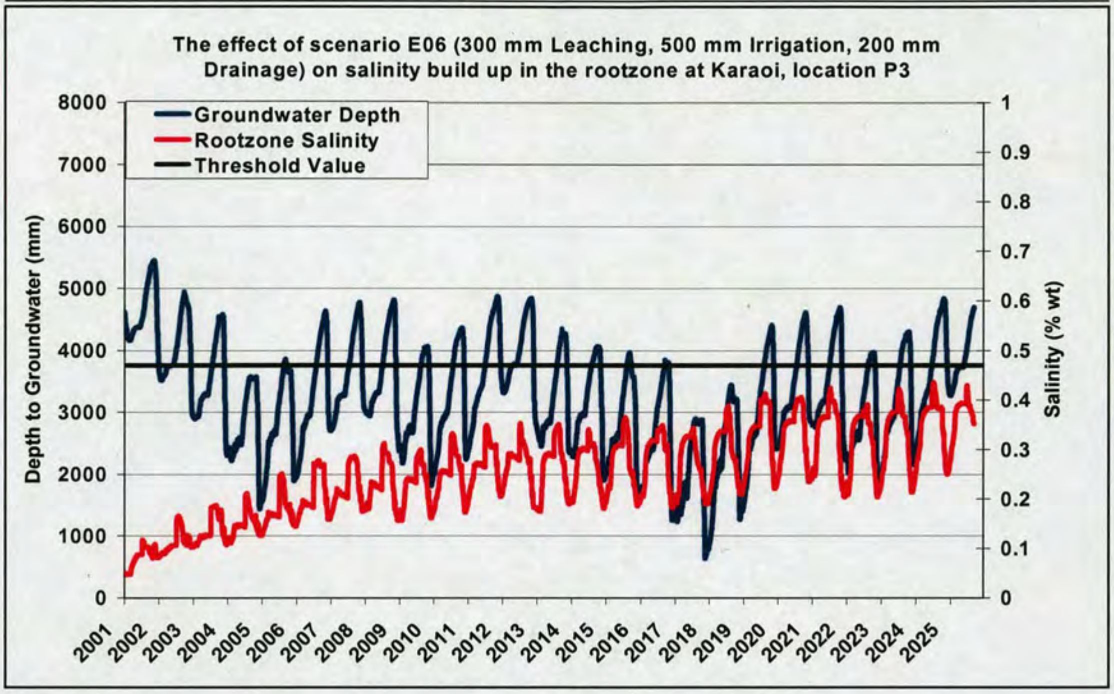


Figure 7.16: Salinity build up in the rootzone under scenario of relatively high water application and low drainage at Karaoi area, location P3

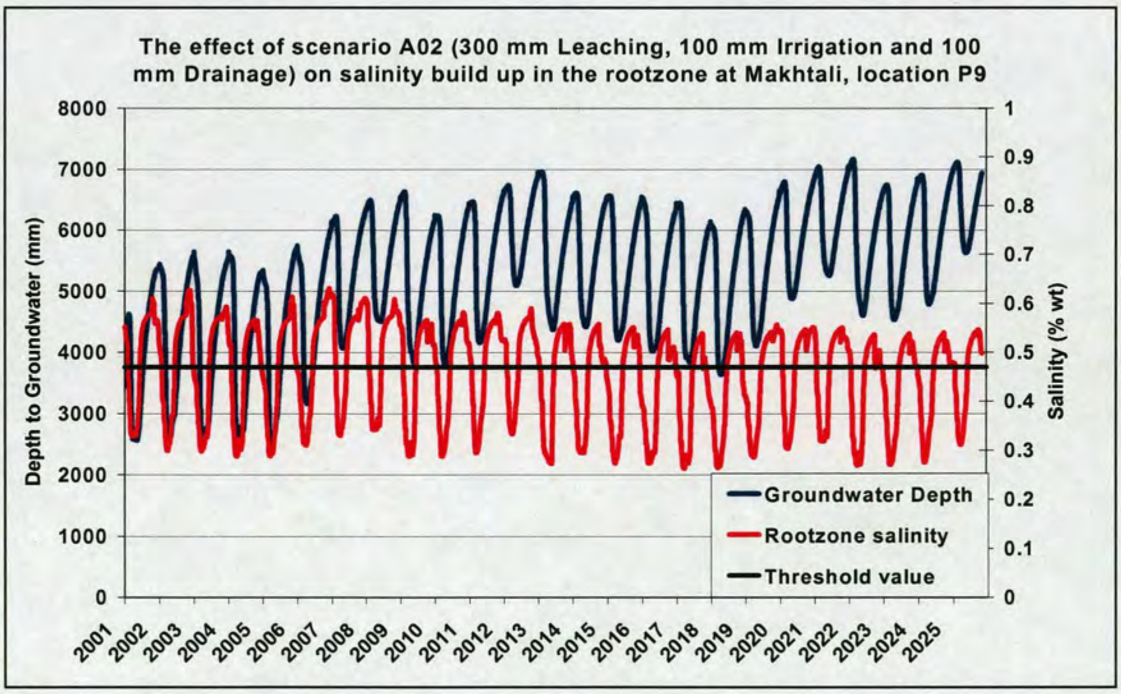


Figure 7.17: Salinity build up at Makhtali area, location P9 under conditions of low water applications and low drainage

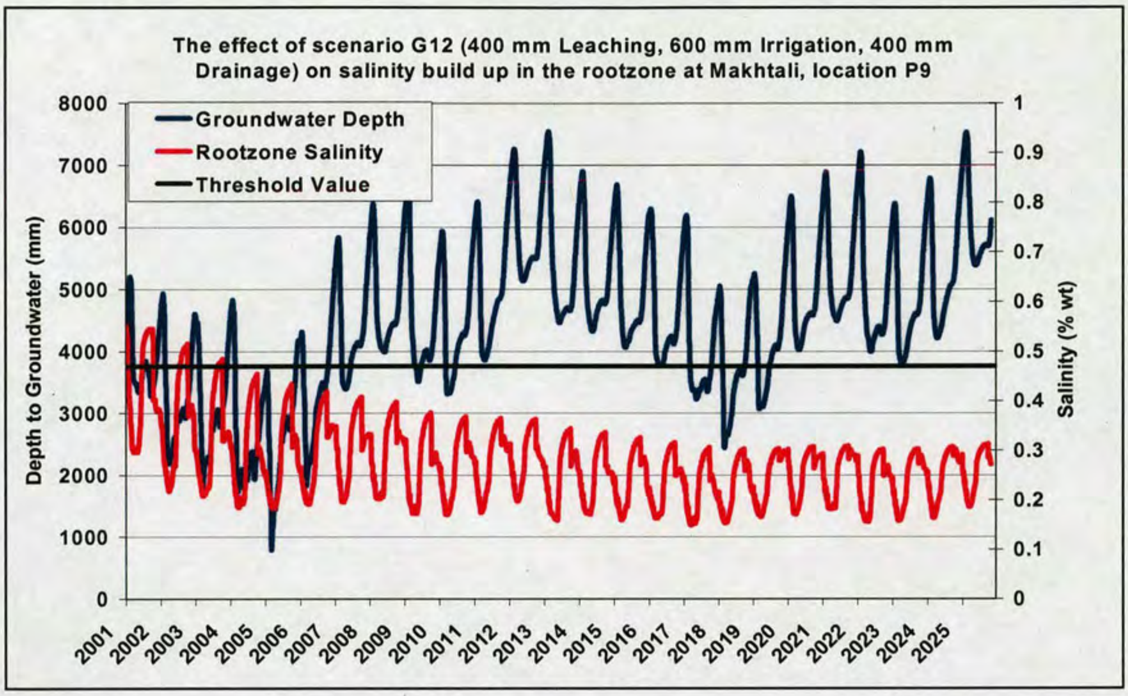


Figure 7.18: Salinity build up at Makhtali area, location P9 under adequate irrigation and drainage combinations

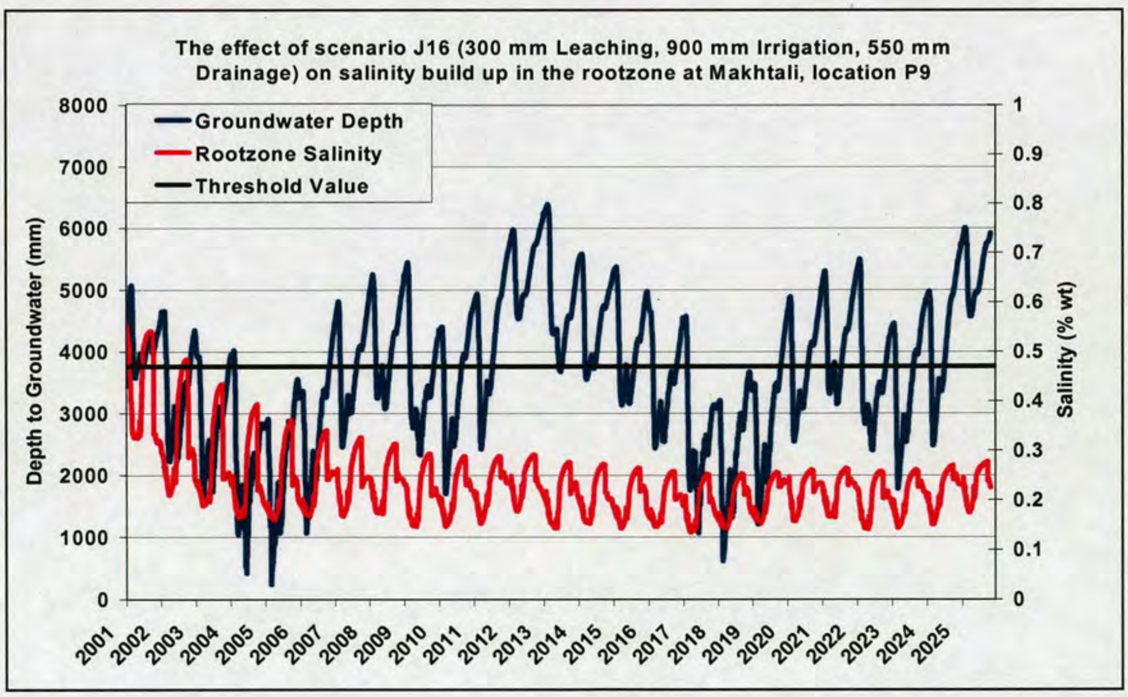


Figure 7.19: Salinity build up at Makhtali area, location P9 under optimum irrigation and drainage combinations

In the Birlik area, the initial soil salinity was high. Figure 7.20 shows that soil salinity decreased during the first year of simulation even under a low drainage rate. However, salinity remains above the salt-tolerance threshold for part of the time in every year, resulting in some salinity stress. Figure 7.20 is similar to Figure 7.17 in that root zone salinity appears to be in dynamic equilibrium. However, crop yields would be very low as a result of water stress. Figure 7.21 shows the effect of optimum irrigation, leaching and drainage combinations on salinity build up in the rootzone as well as on watertable depth. This optimum scenario of 550 *mm* per annum drainage has led to sharp decrease in soil salinity in the rootzone from the initial value during the first years of simulation. Under this scenario, soil salinity remained under 0.3% over the last ten years of simulation with no impact on crop transpiration and yield. The penalty is of course water applications are of the order of 1200 mm in order to produce maximum crop yields.

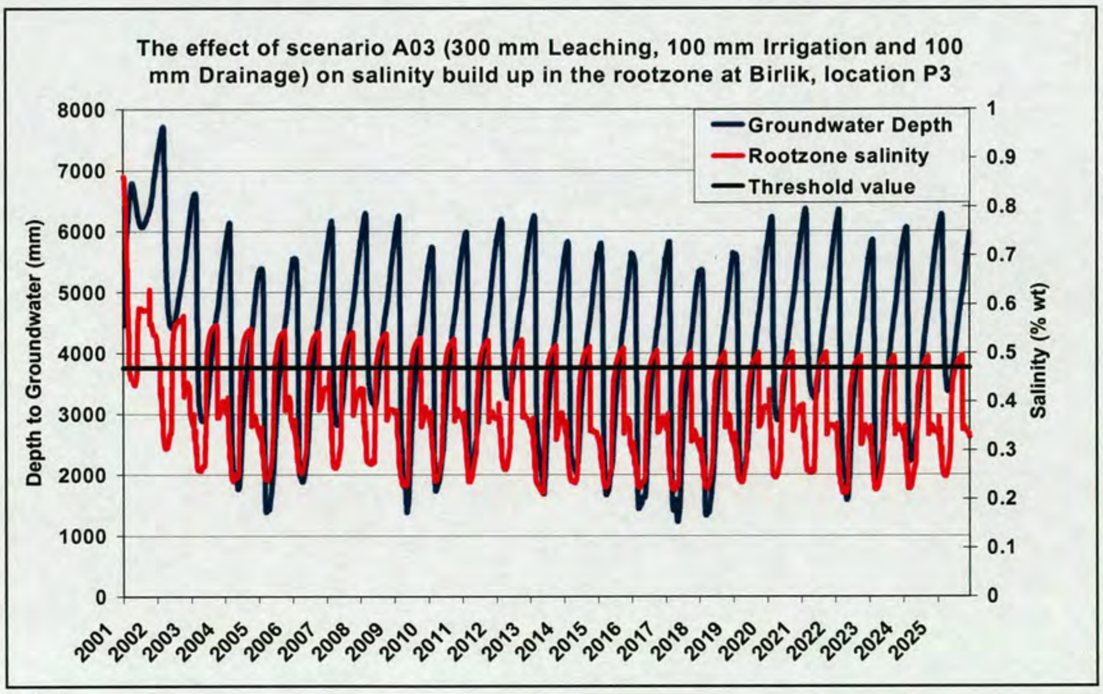


Figure 7.20: Salinity build up at Birlik area, location P3 under low drainage scenario

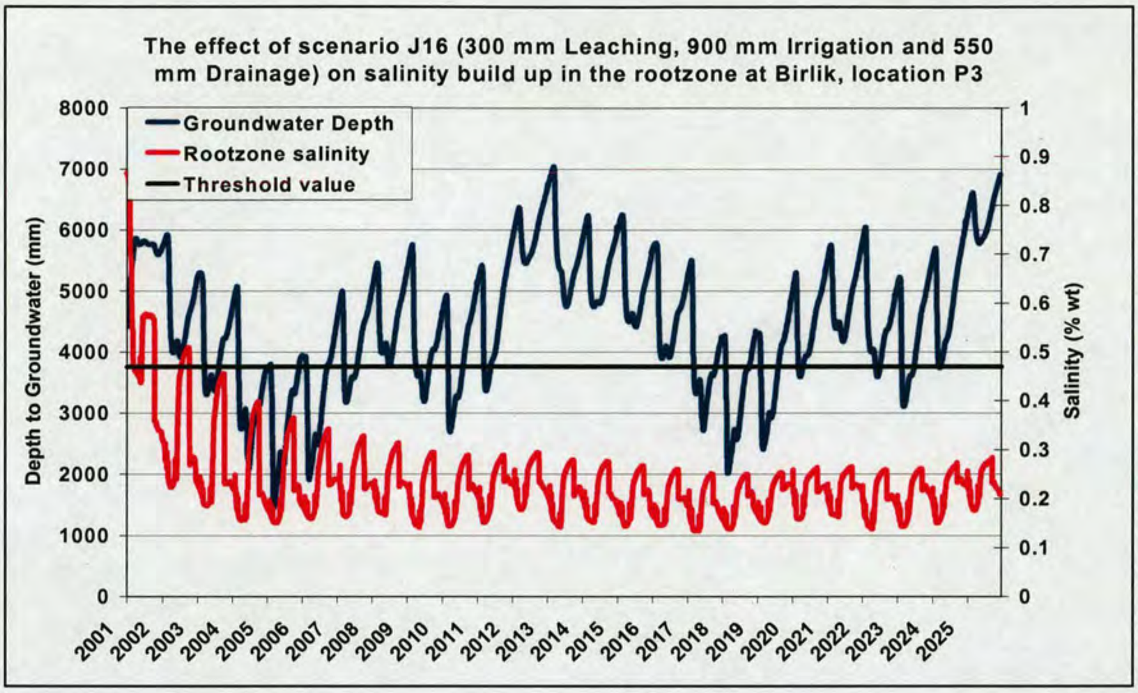


Figure 7.21: Salinity build up at Birlik area, location P3 under optimum irrigation and drainage combinations

7.4.3 Crop Yield

The combined effects of water stress, salinity and water logging on crop yield at each representative site, along with other assessment parameters, are presented in Appendix D for each pilot area. A large number of combinations of water supply, leaching amount and drainage rate produce yields of >80%. However, with scenarios of low drainage, crop yields in the Makhtali and Birlik pilot areas continue to decline as a result of salinity build up in the rootzone. To achieve a high yield in these areas requires annual water supply of at least 1000 *mm* along with drainage of at least 400 *mm*. Figure 7.22 shows the decline in crop yield at Makhtali due to salinity stress under scenarios of low drainage. In the Karaoi area, as there was no salinity effect, there was no decline in crop yield and a high average yield over the last 10 years of simulation can be achieved even with a water application of about 800 *mm* and annual drainage of about 300 *mm*. Karaoi is close to the collector drain and natural drainage is therefore good. However, under such low water applications and low drainage, there is a significant increase in the soil salinity and a decline in crop yield would occur eventually when the salinity level exceeds the threshold value. Figure 7.23 shows simulated cotton yield at Karaoi, location P3. The Simulation results also indicate that, the effect of water stress on crop yield is more significant than the effect of salinity stress. There are scenarios that can produce stability in salinity levels with only modest salinity stress, but these are generally associated with low irrigation applications and significant water stress.

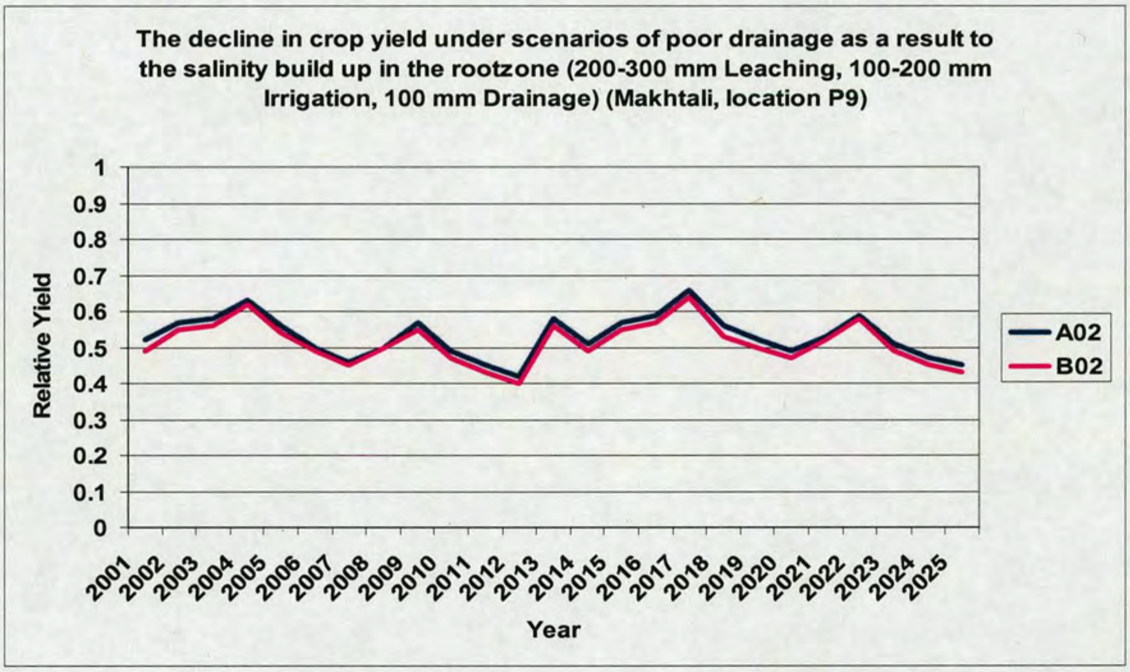


Figure 7.22: Crop yield at Makhtali under low water application and poor drainage

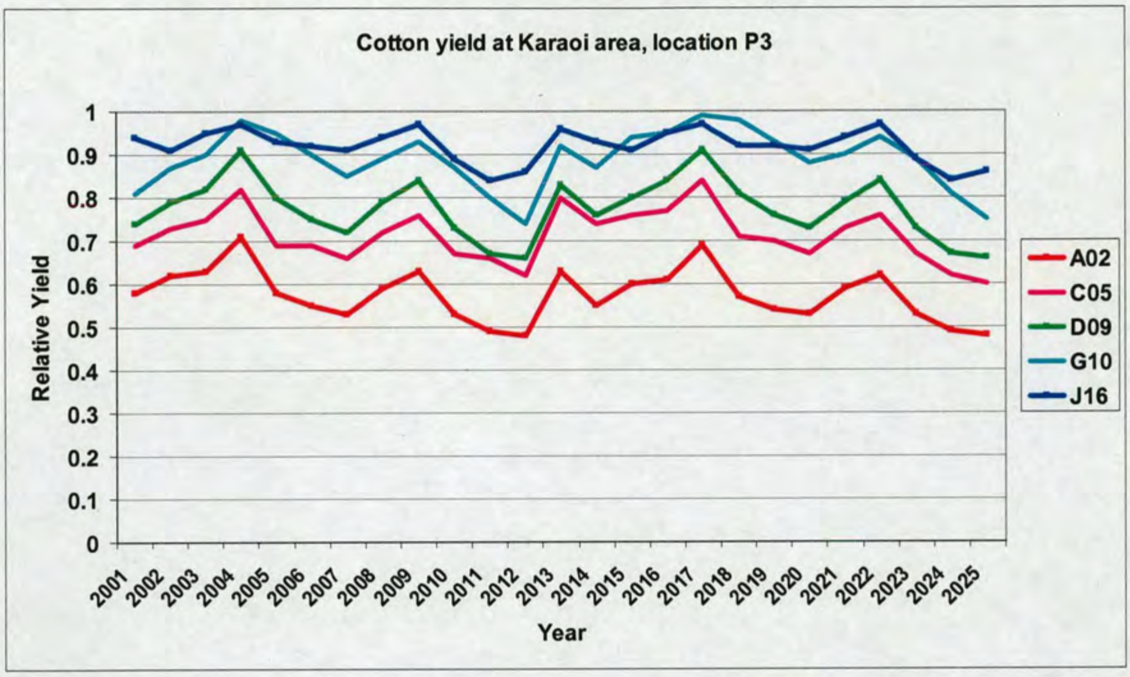


Figure 7.23: Simulated cotton yield at Karaoi, location P3 under different scenarios

To examine the influence of drainage timing on crop yield, scenarios that apply the same amount of leaching and irrigation and only differ in the timing of drainage were compared. Figure 7.24 shows the effect of drainage timing on the simulated crop yield at Karaoi. Results indicate that timing of drainage is not important and it has only a slight impact on simulated yield. Scenarios providing continuous drainage over 12 months (G10, H10, I19) produce slightly higher yield than those providing drainage only in 5 or 6 months (G11, G12, H11, I20, I21). The differences in yield are attributed to the slight effect of waterlogging under the scenarios providing drainage for only 5 or 6 months. Under some scenarios (especially those with 1000 *mm* water applications H10 and H11) timing of drainage has no effect on simulated crop yield as there was no waterlogging problem.

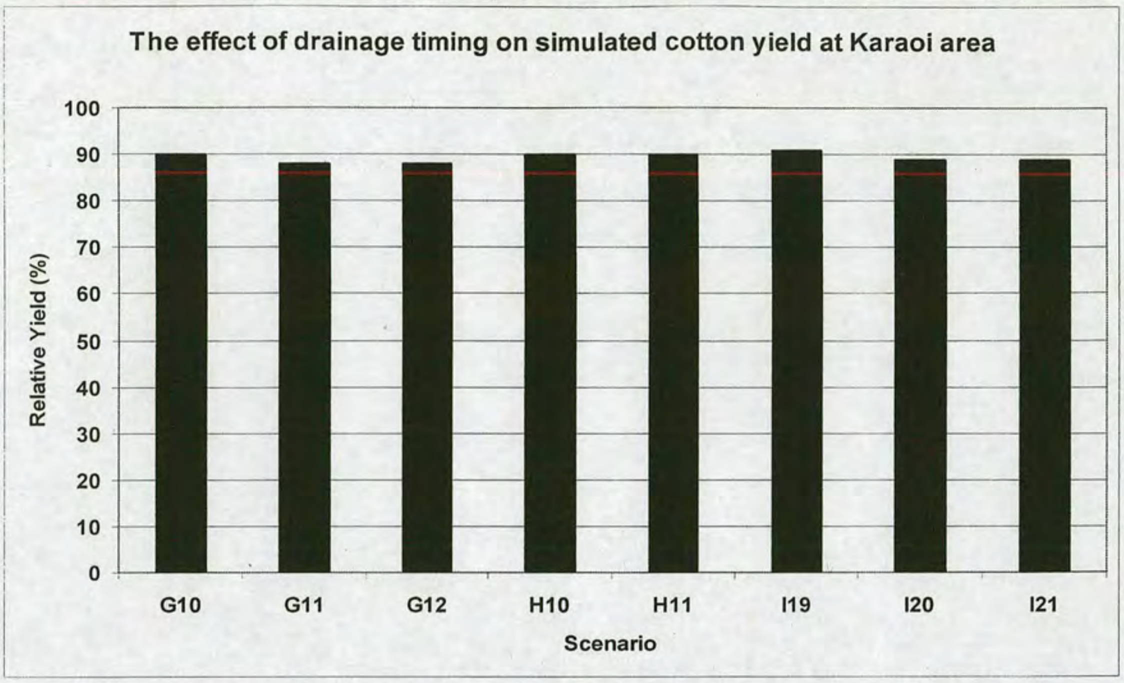


Figure 7.24: The effect of drainage timing on crop yield at Karaoi area, location P3

7.4.4 Sustainability

Irrigated agriculture in arid and semi-arid regions often has negative environmental impacts. The main challenges for sustainable irrigated agriculture in arid and semi-arid regions are in preventing soil salinity, water logging and other soil degradation processes. In arid and semi-arid regions, maintaining soil salinity at acceptable levels for crop production generally requires adequate leaching and the provision of efficient drainage.

The sustainability of agriculture in arid and semi-arid regions depends on the salt concentration in the soil profile (Stamford *et al.,* 2002). According to Denison *et al.,* (2004), sustainable agricultural production means achieving acceptable levels of crop yield over the long-term without any damage to the soil. In other words, it may be defined as the ability to produce adequate food from irrigation agriculture, without harming soil and water resources, or the environment. For example, practices that lead to waterlogging and/or significant increase in soil salinity, which in turn lead to a decrease in the crop yield, are unsustainable. When parameters or criteria are selected to evaluate agricultural sustainability, there should be no trends in these parameters (Rasul and Thapa, 2004). In the evaluation of the simulated irrigation and drainage scenarios considered in this thesis, sustainability is assessed on the basis of long-term trends in rootzone salinity. The recent irrigation and drainage practice in the Makhtaaral Region of Kazakhstan is an example of unsustainable practice that caused a dramatic increase in soil salinity and resulted in reduced crop yield. If current irrigation and drainage practices in this area were to continue, significant environmental and economic damage would result from a rising watertable, soil salinisation, and waterlogging. Crop yields would continue to decline.

The sustainability of irrigation and drainage scenarios must be considered along with the crop return per unit of water applied and per unit of drainage. In the modelling procedure of this research, crop return per unit of water applied and unit of drainage is evaluated through the Cost-Benefit Index, as discussed in section 7.3.2. Some scenarios can be sustainable but they are not economic as the crop return per unit of water and unit of drainage (Cost-Benefit Index) is low. The higher the Cost-Benefit Index the higher the crop returns per unit of water applied and unit of drainage. Appendix E presents the simulation results in terms of sustainability and Cost-Benefit Index.

Simulation results indicate that, in the Makhtali and Birlik areas, many irrigation, leaching and drainage combinations with yields of > 80% can be sustainable as soil salinity in the rootzone under these scenarios is kept stable and below the threshold value. Figure 7.25 and 7.26 show comparisons between selected sustainable scenarios in terms of Cost-Benefit Index at Makhtali and Birlik respectively. On the basis of this comparison, it is obvious that scenario J16 at Makhtali and Birlik have the highest Cost-Benefit Index and can be chosen as an optimal irrigation and drainage combination. Some scenarios of low crop yield achieved sustainability, for example, A02, A03, B02 and B03 are sustainable but the Cost-Benefit Index is low.

The Cost-Benefit Index of the other scenarios used in the comparison is relatively high because crop yield under these scenarios is high.

In Karaoi, many irrigation, leaching and drainage combinations achieved high yields as well as high Cost-Benefit Index. For example, scenario J19 achieved 92% of the potential yield with Cost-Benefit Index of about 88. However, there was a significant increase in the rootzone salinity under all scenarios and none of the combinations achieved sustainability. Tables 7.5, 7.6 and 7.7 provide a summary of model results for Karaoi, Birlik and Makhtali areas respectively.

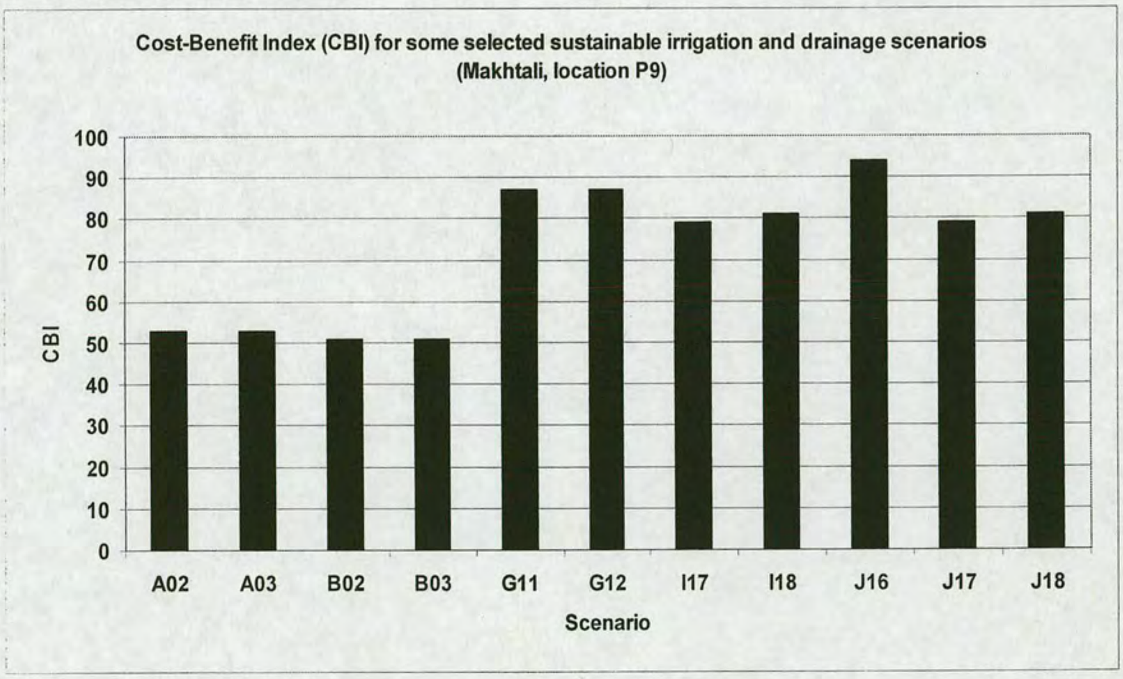


Figure 7.25: Cost-Benefit Index for some selected scenarios (Makhtali, location P9)

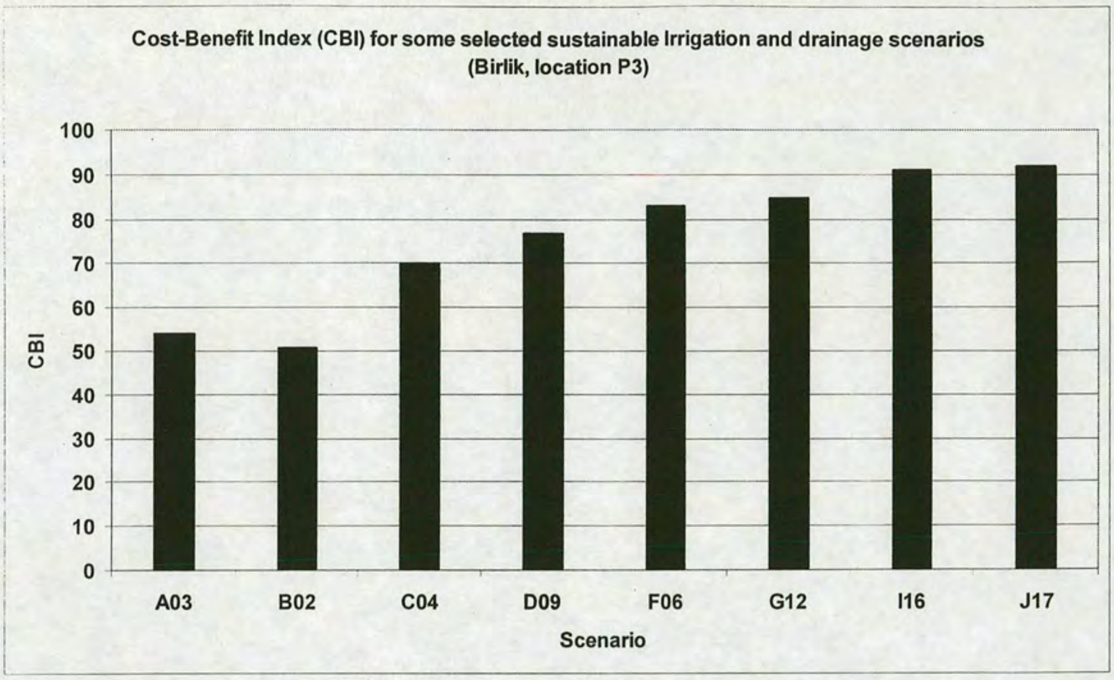


Figure 7.26: Cost-Benefit Index for some selected scenarios (Birlik, location P3)

Table 7.5: Summary of model results, Karaoi soil characteristics

Scenario	Results
A02, A03	Insufficient water supply, no salinity or waterlogging problems. However, salinity increases significantly due to low drainage rates. Low yield of 56%-63%. Unsustainable.
B02, B03	Inadequate water supply, no salinity or waterlogging problems. Salinity increases significantly due to low drainage rates. Low yield of 58%. Unsustainable.
C05, C06	Insufficient water supply. Inadequate drainage resulting in significant salinity builds up. Average yield of 70% has been achieved. Unsustainable.

D07, D08, D09	Yields about 77%-80%, constrained by water supply, no salinity or waterlogging problem. Significant salinity build up. Unsustainable.
E05, E06, F06	Soil salinity is below the threshold value, high average yield of 88% has been achieved; soil salinity increases significantly due to inadequate drainage. Unsustainable.
E07, E08, E09 F07	Reduced yield of about 76%-79% because drainage too high. There is still significant increase in rootzone salinity. Unsustainable.
G10, G11, G12, H10, H11	High average yield of 88% - 90% has been achieved. No salinity or waterlogging effect. Salinity build up in rootzone is relatively slow. There is still need to increase drainage rates. Unsustainable.
I19, I20, J19	Adequate water supply and no salinity or waterlogging problem. Unsustainable practice as there was soil salinity increases very slightly over the simulation period. High yield of 89%-93%. Cost-Benefit Index 85-89.

Table 7.6: Summary of Model results, Birlik soil characteristics

Scenario	Results
A03	Progressive yield reduction due to salinity and inadequate water supply. Although, this scenario achieved sustainability, soil salinity is still above the threshold value due to inadequate drainage rate. Low yield of 55%.
B02	Inadequate water supply, and inadequate drainage resulting in salinity build up and declining yields. Sustainable yield of 52%.

C04, C05	Sustainable practice. Inadequate water supply, no salinity problem over the last 10 years. Average yield of 71% has been achieved.
D07, D08, D09,	All are sustainable. Inadequate water supply, there is no waterlogging or salinity problem. Water stress is the only effecting factor on crop yield. Sustainable high yields of 79%.
F05, F06	Sustainable practice. There was waterlogging problem in addition to water stress. Average yield is about 85%.
G10, G11, G12	Sustainable yield of about 88%. Insufficient water supply, reduction in yield is due to water stress only. Relatively high Cost-Benefit Index of 85.
I16	Sufficient water supply, and adequate leaching and drainage resulting in high yield of 95%. High Cost-Benefit Index of 91.
I17, I18	85% average yield. Waterlogging problem exist. These scenarios achieved relatively high Cost-Benefit Index of about 84.
J16, J17	Adequate water supply. Slight waterlogging problem exist in some years. Very high yields of 96%-98% have been achieved. These scenarios achieved the highest Cost-Benefit Index of 92-94.

Table 7.7: Summary of Model results, Makhtali soil characteristics

Scenario	Results
A02, A03, B02, B03	Water applications are inadequate. Although these scenarios are sustainable, they achieved low yield of 52%-54%. Salinity is remained stable above the threshold value. Low Cost-Benefit Index.
G11, G12	Sustainable high yield of 90% has been achieved. No waterlogging or salinity problems. The reduction in yield is attributed to water stress.

I17, I18	Sufficient water application and no salinity problem. 16% yield reduction due to waterlogging problem.
J16	High average yield of 98%. No salinity or waterlogging problems. Highest Cost-Benefit Index of 94.
J17, J18	Reduced yield of 83% due to water logging problem.

7.4.5 Identifying the optimum irrigation and drainage scenarios

On the basis of the analysis given in the previous sections, the irrigation and drainage scenarios resulting in highest sustainable yields require 300 – 400 *mm* leaching and 800 - 900 *mm* irrigation, accompanied by 550 *mm* of drainage. This amount is sufficient to meet the crop water requirements, keep soil salinity in the rootzone under control and below the critical value for salinity stress, and produce a sustainable relative crop yield >85%. Figure 7.27 presents crop yield under one of the chosen irrigation and drainage scenario in the Birlik area. The scenario is sustainable, kept soil salinity around 0.30% and produced an average crop yield of about 98% over the last 10 years of simulation. According to these results, crop yield response to irrigation and drainage management in the project area can be improved and efficient strategies can be identified but largely due to the fact that the cost of irrigation and drainage is very low relative to the crop return, and probably not economic. Figure 7.28 shows the effect of the proposed scenarios on crop yield at Makhtali areas. Even though there was waterlogging problem in early years of the simulation period, soil salinity was kept under control around 0.30% and 98% of potential yield has been achieved over the last 10 years of simulation.

In Karaoi, initial soil salinity values at the start of the simulation were very low. As a result, there was an increase in soil salinity over the simulation period even under scenarios of high water application and high drainage rate. Another run was carried out in which soil salinity value at the end of the simulation period was used as initial value. It has been found that, soil salinity levelled out below the threshold values and many scenarios of high water application and high drainage rate are sustainable. With Karaoi characteristics, 600 *mm* drainage is required along with 300 *mm* leaching and 900 *mm* irrigation. Figure 7.29 shows the effect of optimum irrigation and drainage combinations on salinity build up in the rootzone. This scenario achieved very high cotton yield of 94% with Cost-Benefit Index of 90. This is demonstrated in Figure 7.30.

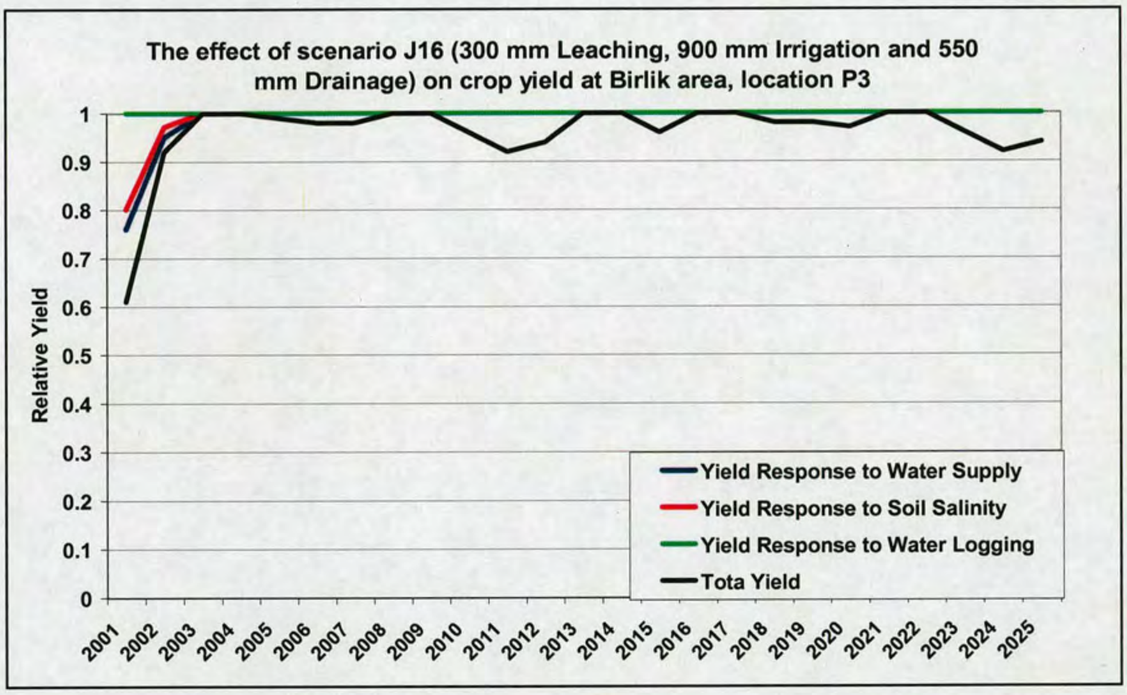


Figure 7.27: The effect of the recommended scenario on crop yield at Birlik, location P3

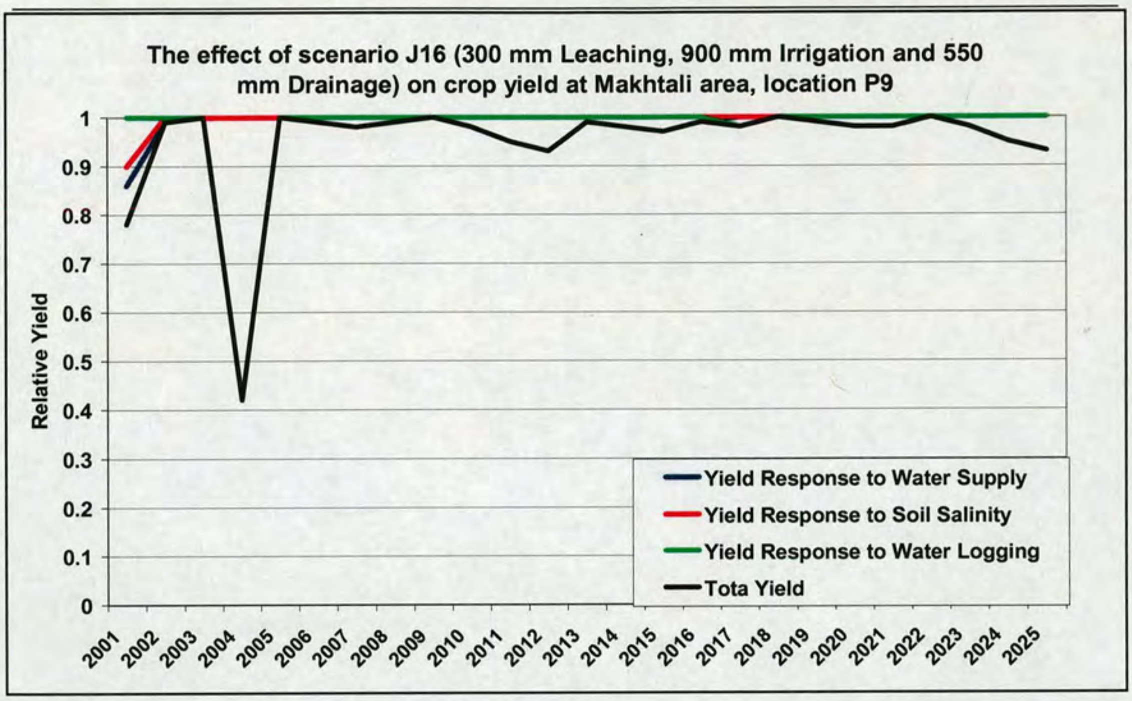


Figure 7.28: The effect of the recommended scenario on crop yield at Makhtali, location P9

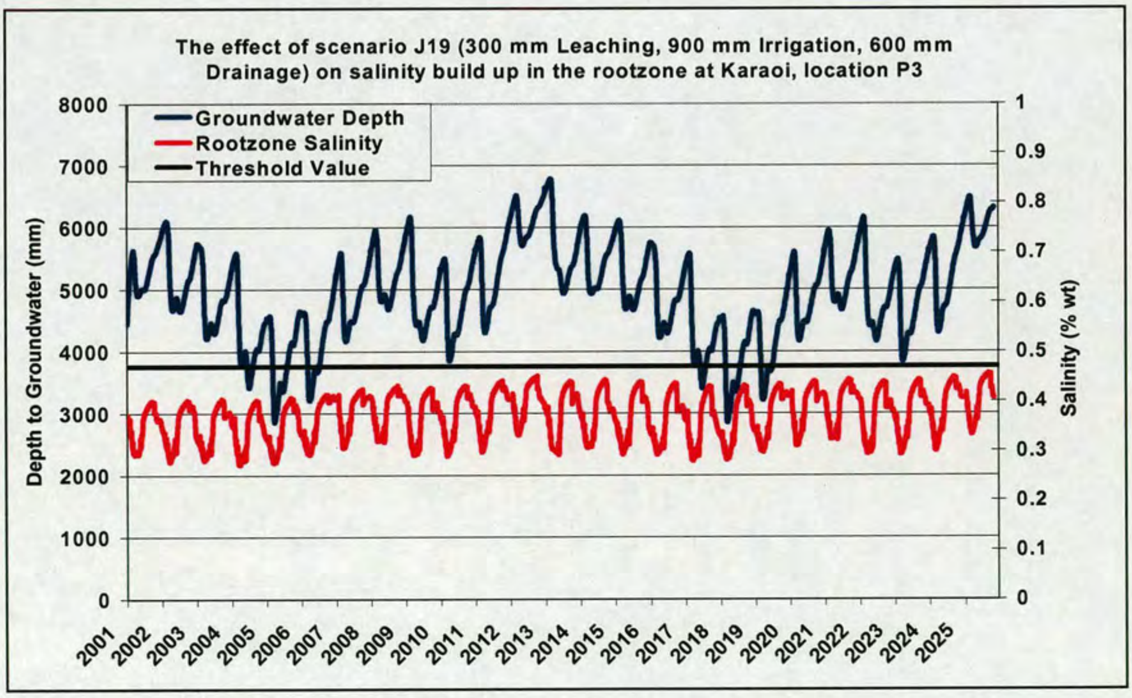


Figure 7.29: Salinity build up in the rootzone under optimum irrigation and drainage combinations at Karaoi area, location P3

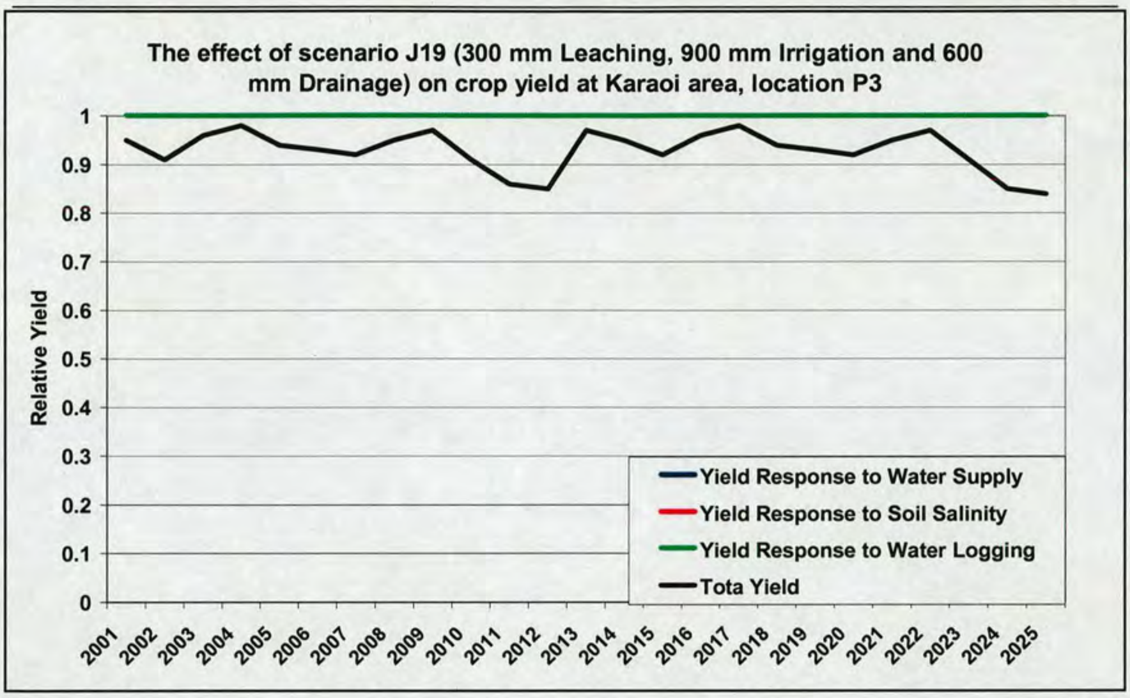


Figure 7.30: The effect of the recommended scenario on crop yield at Karaoi, location P3

7.4.6 Wider Issues

The optimal irrigation and drainage scenarios all require significantly higher water applications than has been possible with available resources in recent years. Recent main canal diversions (controlled in Uzbekistan) would not be sufficient to provide the project with the required amount of water required for optimal cropping, especially during sensitive crop stages. With the amount of water available for irrigation in recent years (400-500 mm), sustainable scenarios are possible, but not with a reasonable Cost-Benefit Index described, could be applied. Typically yield losses through water stress would be of the order of 50%. The lowest amount of water required for a sustainable scenario with a high Cost-Benefit Index in the Makhtali area is 1000 mm (scenario G11 and G12), which is significantly higher than the amounts recently available. This scenario achieved 90% of potential yield with Cost-Benefit Index of 87. At Birlik the lowest amount of water required for sustainable crop production at an acceptable return is 600 mm (Scenario C04 and C05), which is still higher than the amount available.

There is clearly an urgent need for international agreement to increase water deliveries to the project from the Syr Darya River in order to apply the results achieved through this research. It should be noted of course that had higher deliveries been made in recent years in the absence of drainage, soil salinity would be much worse than it now is.

Irrigation from both the Syr Darya and the Amu Darya rivers has caused significant environmental damage to the Aral Sea, which is well documented, and to the irrigated lands which were affected by salinity due to poor drainage. In downstream areas, more than 50% of the irrigated lands are classified as moderately to highly saline. The effect on the environment of the Aral Sea basin includes changes in temperature and precipitation. Temperature increased by just less than 1 $°C$, and the annual total precipitation reduced by 16 *mm* (Cai *et al.,* 2003). Increasing water withdrawal from the river will impact on flow release to the Aral Sea, but on the other hand a significant population is now dependent upon irrigated agriculture, and much of the damage to the Aral Sea is probably irreversible. A dam is currently being constructed across the sea to maintain a smaller but more permanent water body.

It is, however, necessary to explore alternative water resources management and to decrease if possible abstractions from the Syr Darya River. Cropping patterns could be changed for example and farmers encouraged to concentrate on crops with lower water requirements than cotton. This is also recommended by Cai *et al.,* (2003). They suggested reducing the area planted with cotton, from 60% to 40% of the total irrigated area. Cotton is a high salt tolerance crop but has high water consumption. The area planted with wheat and maize could be increased from 10% to 32% of the total irrigated area.

7.5 Conclusions

In this chapter, the model runs carried out in the evaluation of the current irrigation and drainage practices were presented. According to the results of these runs, cotton yield in the area would be reduced to a very low level within 25 years if irrigation and drainage practices are not changed. Inadequacy in water applications and increasing soil salinity are brining about this reduction.

The main objective of this research has been achieved as efficient sustainable irrigation and drainage strategies have been identified. The WAVE_MS model along with C_YIELD, has been used to assess long term impact of alternative irrigation and drainage scenarios on crop transpiration, salinity build up in the rootzone and subsequently on crop yield. The objective was to produce a high sustainable crop yield per unit of water applied and unit of drainage. Low water application and low drainage can be sustainable but crop yields would be very low (less than 50% of potential). The best cotton yield would be achieved with water applications of about 1200 *mm* accompanied with annual drainage of 550 *mm*. In addition, leaching applications should not be less than 200 *mm*. The timing of drainage is not important, but providing continuous drainage over 12 months produces slightly higher yield than when drainage is only provided for 5 or 6 months of the year. In the Karaoi area 600 *mm* annual drainage is required for sustainability.

Available water is not sufficient at the present time to provide the project with the required irrigation water, especially during the sensitive crop stages. Accordingly, there is an urgent need for international agreement to increase water deliveries to the project from the Syr Darya River. This may not be possible due to the environmental problems associated with excessive depletion from the Syr Darya River. The cropping pattern could be changed to crops of low water requirements. The area planted predominantly with cotton, which has a high water requirement but is salt tolerant. The area of cotton could be reduced and the area planted with wheat and maize increased.

The conclusions drawn above are subject to the limitations of model calibration that have been highlighted in Chapter 6. Confidence in model calibration is limited by the number and quality of soil moisture tension and salinity data. This may influence the reliability of simulations of soil water and salinity stress on crop transpiration and yield. More frequent field data of good quality are required to validate the simulation results presented in this chapter.

CHAPTER 8

Conclusion

8.1 Introduction

The research carried out for this thesis investigated the implementation of mathematical modelling techniques for irrigation water management. The improvement of the WAVE model and application of the WAVE_MS model to the Makhtaaral region of South Kazakhstan has been presented and its effectiveness in identifying optimal irrigation and drainage water management strategies that maximise crop yield has been analysed. WAVE_MS model performance has been evaluated against field data collected from pilot areas in Makhtaaral. This chapter summarises the research reported in this thesis, outlining the limitations of the research and making recommendations for further work.

Following this introduction, section 8.2 presents the achievement of the research. Section 8.3 outlines the limitations and section 8.4 presents recommendations for further work.

8.2 Achievement of the Research

The research presented in this thesis is made up of three main parts. The first part of the thesis presented the improvements made to the WAVE model. The second part investigated the model performance in predicting soil moisture and salinity levels in the vadose zone. Finally, the WAVE_MS model was applied in the evaluation of the current irrigation and drainage practices and in the establishment of optimal irrigation and drainage strategies for the Makhtaaral region of South Kazakhstan. Major achievements of the thesis and the contributions of each part are presented below.

Chapter 2 of the thesis presents a review of the basic concepts of evapotranspiration estimation procedures, the most important crop yield response functions, and the effect of water and salinity stress on crop growth and yield. Chapter 3 of the thesis presents an evaluation of some existing crop yield response functions. The relative sensitivity of each of these functions in application with the same water stress is presented. It also provides an examination of the accuracy of the functions in predicting crop yield under different levels of evapotranspiration deficit. In fact many of the functions produce identical results. In a comparison with experimental data, all functions gave reasonable predictions of yield under a range of water stress levels when using published seasonal yield coefficients. It is apparent that all functions would be suitable for yield response modelling. Yield response coefficients are influenced by local conditions, and a wider data set of coefficients than is currently available is desirable.

In Chapter 4 of the thesis, a technical review of several variably saturated flow models is presented. It gives the most important theoretical concepts, discusses limitations and presents applications by researchers. Generally, all models presented have a similar conceptual basis and solve the same equations for simulating water and solute transport. However, WAVES and SWAP require input data that are not always readily available. UNSATCHEM is the only model that accounts for multi-component solute transport with major ion equilibrium and kinetic chemistry in variably saturated flow, and has the ability to quantify crop yield response to water and salinity stress. However, it requires input salinity data in terms of soluble, adsorbed and precipitated salts and these data are not always available. It is not clear from the literature if the SALTMED model is capable of dealing a water table interface. It would appear that it can deal with a free drainage lower boundary or with an impermeable lower boundary, which by implication would result in build up of a saturated zone. There is not, however an ability to deal with controlled drainage, and this may limit its applicability. The WAVE model in its original form does not consider the effect of salinity stress on crop transpiration, which makes it less applicable under salinity conditions. The WAVE and HYDRUS-2D model are also limited in that they do not include crop production functions and are unable to quantify the effect of water and salinity stress on crop yield. However, source code access to WAVE meant that these shortcomings could be addressed.

The WAVE model was selected for use in this research, primarily because of source code access that would permit further model development with respect to incorporating the combined effects of water and salinity stress on actual evapotranspiration, and crop yield. The SWAP model code is now available (but had not been at the start of this research), and in future research it would be of interest to evaluate this model also.

Chapter 5 of the thesis presents a brief review of the theory behind the WAVE model. The modifications made to the model as part of this research are outlined. The modifications have been successful. The test results verify that the WAVE_MS model is now capable of dealing with the combined effects of water and salinity stress as the crop transpiration calculated by the revised model was lower than that calculated using the original version once soil salinity exceeded the threshold value for salinity stress. Full verification of the modified model would require experimental lysimeter data that were not available for this research.

In chapter 6 of the thesis data and parameters used for the model set-up and calibration are discussed in detail. In terms of soil moisture content and soil salinity, the calibration results were satisfactory. However, soil salinity and soil moisture tension calibration was restricted by the number and quality of the data from the pilot area data collection programme. Soil salinity and soil moisture tension calibration need to be improved when more data of good quality become available. The model would require re-calibration when more soil salinity data of good quality become available. An on-going field programme would permit more reliable calibration and validity of the model. The more data of good quality that can be collected the better will be model performance and confidence in model results. Generally, the reasonable agreement between observed and simulated soil moisture gives confidence that the WAVE_MS model can be used to predict long term water balance as well as investigating long-term salinity build up in the root zone and the effect of moisture and salinity stress on crop yield.

Some of the major contributions from the work on WAVE and WAVE_MS are summarised below:

- Two weak points in the original WAVE model were identified. Firstly, it considers only the effect of soil water stress on crop transpiration; it does not take into account the effect salinity. Secondly, it is unable to assess the combined effect of irrigation water applications, leaching amounts, and drainage rate on crop yield since it does not include any crop yield response function in its crop growth module.

- A modified WAVE model called WAVE_MS that is applicable under water shortage and salinity conditions has been developed that includes the effect of salinity on crop transpiration.

- A set of values for the modified WAVE model parameters that provide the best performance in predicting soil moisture content, soil salinity and crop yield in the pilot areas used for the research were determined.

Chapter 7 of the thesis presents the application of the WAVE_MS model to the Makhtaaral region of South Kazakhstan. The objective was to demonstrate the translation of the results of sophisticated modelling approaches into formats that will assist farmers in achieving sustainable management of their land and water resources. From the WAVE_MS simulation outputs, it is clear that the irrigation supply to farmers has been inadequate in recent years. Irrigation applications for cotton have been significantly less than its requirements and there has been water stress during most of the growth period. Were current practices to continue there would be a continued decline in crop yields as a result of water stress and an ever increasing soil salinity. Low water application and low drainage can be sustainable but crop yields would be very low (less than 50% of potential). The best cotton yield would be achieved with water applications of about 1200 *mm* accompanied with annual drainage of 550 *mm*. In addition, leaching applications should not be less than 200 *mm*. The timing of drainage is not important, but providing continuous drainage over 12 months produces slightly higher yield than when drainage is only provided for 5 or 6 months of the year. In the Karaoi area 600 *mm* annual drainage is required for sustainability.

Some major achievements from this part of the research are summarised below:

- The long-term impact of the current irrigation and drainage practices on salinity build up and crop yield in the Makhtaaral region of South Kazakhstan has been demonstrated.

- Efficient and economic irrigation and drainage strategies that maintain and improve crop production in the Makhtaaral region of South Kazakhstan have been identified.

Water supply to the Makhtaaral region from the Doystick canal will have to be increased significantly if optimal crop yields are to be attained in the future. This will require international agreement. It should be noted, however, that had adequate water supplies been available over the last fifteen years, then in the absence of drainage, the salinity problems would in fact have been much worse than they now are. Restoring water supplies to the Makhtaaral region will contribute further to negative impacts in the downstream reaches of the Syr Darya River, and on the Aral Sea. Consideration should be given to changing cropping patterns and introducing crops with lower water requirements. A large number of people are, however, dependent upon irrigation in the Makhtaaral region for their livelihoods, and their welfare is central to future planning. Subsidies may be required to encourage changes in cropping.

8.3 Limitations of the Research

In the evaluation of crop yield response functions, the accuracy of these functions in predicting crop yield under different levels of water stress was examined using experimental evapotranspiration and yield data from New Zealand. No such data were available for Kazakhstan. The parameters of these functions can be location specific. The check against the New Zealand data indicated that the yield response functions produce reasonable but conservative results when used with published yield response coefficients. More reliable yield response assessments require experimentation on crop transpiration and yield under water and salinity stress in South Kazakhstan.

Although Mott MacDonald initiated an extensive field data collection programme on three pilot areas, the data collected on soil moisture tension and soil salinity were few and of poor quality. This led to some calibration difficulties and may influence the reliability of simulations of soil water and salinity stress on crop transpiration and yield. Relative results between different simulation runs with the same parameter sets should, however, be reliable.

8.4 Recommendations for Further Research

To conclude the thesis, the following recommendations are made for further research which could lead to more efficient water resources operation and management for irrigation in arid and semi-arid regions, and for the Makhtaaral region of Kazakhstan in particular.

8.4.1 Field Data Collection

In the Makhtaaral region, WAVE_MS model calibration was constrained by the limited number and quality of soil moisture tension and salinity data available. More frequent and careful monitoring of these field data are required. An on-going field programme would permit the validity of the simulation results to be re-assessed. The more data of good quality that can be collected the better will be model performance, and the value of predictions and management strategies produced.

8.4.2 Crop Transpiration

There is a need for further research into the validity of the functions to determine the effects of water and salinity stress on crop transpiration. Few data could be found in the literature that would permit validation of the functions. Lysimeter experiments should be conducted for a cotton crop to investigate the effects of different levels of water and salinity stress on crop transpiration, and to permit validation of model parameters.

A further recommendation is to use a multi-species salinity model. The objective is to develop a better understanding of the effect of individual salt ions on crop transpiration and yield. The electrical conductivity of the saturated soil extract (EC_e) is commonly used to assess the influence of salinity on crop yield and location specific relationships between EC_e and the total dissolved salts present can be developed. Clearly the species of salts present has a significant bearing on conductivity. However, a more deterministic approach in which EC_e, or osmotic pressure, is related directly to the species of salts present is preferable. An intention of this research was to use the UNSATCHEM model (Simunek *et al.,* 1996). However, the data collected in relating to individual salt ion concentrations present in the soil, included no information on the proportions soluble, adsorbed or precipitated salts, which are required as input for the UNSATCHEM model.

8.4.3 Crop Yield

When considering detailed crop yield studies and crop yield response to different levels of water stress during the different growth stages, a more inclusive approach is required, including the effects of fertilizer and pesticide application. A number of models do include crop growth modules, and combining these with the yield response functions developed for the WAVE_MS model would be valuable.

8.4.4 General Modelling Capability

The modelling approach developed in this research with the WAVE_MS model offers significant potential in the development of sustainable irrigation and drainage management strategies. Parameterisation of the WAVE_MS model, and other similar models, is difficult, however. Improvements are required in the way in which soils data are collected, and there is scope for the introduction automated approaches to model calibration. It would also be very valuable to carry out a series of model parameter sensitivity trials in order to identify clearly how sensitive crop transpiration is to variations in the key soil parameters.

The UNSATCHEM model accounts for the effect of multi-species salinity on crop transpiration and yield, but surprisingly does not consider the amount of solutes that can be added to the soil profile through irrigation water. This makes it less applicable in areas where irrigation water is not of good quality. In addition, UNSATCHEM is limited to a maximum simulation period of only 400 days. Moreover, the model uses the Stewart crop yield response function (Stewart *et al.,* 1976) but assumes that the sensitivity of crop yield to water stress is constant and equal to 1.0. Different sensitivity to water deficits in different growth stages is ignored. The UNSATCHEM model was in fact set up using WRMLIP data, but was not robust and prone to unexplained crashes.

The WAVE_MS model requires lesser data on crop, soil and climatic data than other models. The WAVE_MS model was found to be robust in simulating water and solute transport in the rootzone and had adequate capabilities in crop yield simulation when it linked to the crop response model. It offers wide range of options to identify most efficient irrigation and drainage management as it integrates soil moisture, crop transpiration, water table and solute transport on a daily basis. Verification of the simulated effects of salinity on actual evapotranspiration was not possible, and an experimental lysimeter is required to provide appropriate data.

References

Abu-Awwad, A. M. (2001). "Influence of different water quantities and qualities on lemon trees and soil salt distribution at the Jordan Valley." *Agric. Water Management*, 52: 53-71.

ADB (Asian Development Bank). (1997). Report and recommendations of the President to the Board of Directors on Proposal Loans and Technical Assistance Grant to the Republic of Kazakhstan for the Water Resources Management and Land Improvement Project. Manila, Philippines.

Al-Jamal, M. S., Sammis, T. W., Ball, S., Smeal, D. (2000). "Computing the crop water production function for onion." *Agric. Water Management,* 46: 29-41.

Al-Jamal, M. S., Ball, S., and Sammis, T. W. (2001). "Comparison of sprinkler, trickle, and furrow irrigation efficiencies for crop production." *Agric. Water Management*, 46: 253-266.

Allen, R. L., Raes, D., and Smith, M. (1998). "Crop Evapotranspiration: Guidelines for computing crop water requirements." Irrigation and Drainage Paper No. 56, FAO, Rome, Italy.

Asch, F., and Wopereis, M. (2001). "Response of field-grown irrigated rice cultivars to varying levels of floodwater salinity in a semi-arid environment." *Field Crop Research,* 70: 127-137.

Atis, E. (2004). "Economic impact on cotton production due to land degradation in the Gediz Delta, Turkey" *Land Use Policy,* In Press.

Ayars, J. E., Phene, C. J., Hutmacher, R. B., Davis, K. R., Schoneman, R. A., Vail, S. S., and Mead, R. M. (1999). " Subsurface drip irrigation of row crops: a review of 15 years of research at water management research laboratory." *Agric. Water Management*, 42: 1-27.

Ayers, R. S., Westcot, D. W. (1985). "Water quality of agriculture." FAO Irrigation and Drainage Paper No. 29, FAO, Rome, Italy.

Baes, C. F., and Sharp, R. D. (1983). "A proposal for estimation of soil leaching constants for use in assessment models." *Environmental Quality,* 12: 17-28.

Bassil, E. S., and Kaffka, S. R. (2002). "Response of safflower (*Carthamus tinctorius* L.) to saline soils and irrigation: I. Consumptive water use." *Agric. Water Management,* 54: 67-80.

Belmans, C., J. G. (1983). "Simulation of the water balance of a cropped soil: SWATRE." *Journal of Hydrology*, 63: 271-286.

Benyamini, Y., Mirlas, V., Marish, S., Gottesman, M., Fizik, E., and Agassi, M. (2005). "a survey of soil salinity and groundwater level control systems in irrigated fields in the Jezre'el Vally, Israel." *Agric. Water Management,* 76: 181-194.

Bergstrom, L., Johnsson, H., and Tortensson, G. (1991). "Simulation of nitrogen dynamics using the SOILN model." *Fert. Res.,* 27: 181-188.

Blank, H. (1975). *"Optimal irrigation decisions with limited water."* PhD thesis, Department of Civil Engineering, Colorado State University, Fort Collins, CO.

Boonjung, H., and Fukai, S. (1996). "Effect of soil water deficit at different growth stages on rice growth and yield under upland conditions. 1.Growth during drought." *Field Crop Research*, 48: 37-45.

Botes, J., Bosch, D., and Oosthuizen, L. (1996). "A simulation and optimisation approach for evaluating irrigation information." *Agricultural systems,* 51: 165-183.

Broadbridge, P., and White, I. (1988). "Constant rate rainfall infiltration: a versatile nonlinear model 1. Analytical solution." *Water Resour. Res.*, 24: 145-154.

Brooks, R. H., and Corey, A. T. (1964). "Hydraulic properties of porous media." Hydrology Paper 3, Colorado State University, Fort Collins, CO.

Bucknall, J., Klytchnikova, I., Lampietti, J., Lundell, M., Scatasta, M., and Thurman M. (2003). Irrigation in Central Asia, social, economic and environmental considerations, World Bank Report.

Cai, X., McKinney, D. C., and Rosegrant, M. W. (2003). "Sustainability analysis for irrigation water management in the Aral Sea region." *Agricultural Systems*, 76: 1043-1066.

Cakir, R. (2004). "Effect of water stress at different development stages on vegetative and reproductive growth of corn." *Field Crop Research*, 89: 1-16.

Cardon, E. G., and Latey, J. (1992). "Plant water uptake terms evaluated for soil water and solute movement models." *Soil Sci. Soc. of Am. J.,* 56: 1876-1880.

Cetin, O., and Bilget, L. (2002). "Effects of different irrigation methods on shedding and yield of cotton." *Agric. Water Management*, 54: 1-15.

Champolivier, L., and Merrien, A. (1996). "Effect of water stress applied at different growth stages to *Brassica napus* L. var. *oleifera* on yield component and seed quality." *European Journal of Agronomy*, 5: 153-160.

Chiew, F. H. S., Kamaladasa, N. N., Malano, H. M., and McMahon, T. A. (1995). "Penman-Monteith, FAO-24 reference crop evapotranspiration and Class-A pan evaporation data in Australia." *Agric. Water Management*, 28: 9-21.

Clarke, D., Smith, M., and El-Askari, K. (2000). "CROPWAT 7 and CROPWAT for Windows: Crop water requirements software package." Food and Agriculture Organisation of the United Nations, http://www.fao.org/ag/agl/aglw/cropwat.stm

Cuartero, J., and Fernandez-Munoz, R. (1999). "Tomato and salinity." *Scientia Horticulturae,* 78: 83-125.

Dechmi, F., Playan, E., Faci, J. M., Tejero, M., and Bercero, A. (2003). "Analysis of an irrigation district in northeastern Spain: II Irrigation evaluation, simulation and scheduling." *Agric. Water Management,* 61: 93-109.

Davis, R., and Hirji, R. (2003). "Water resources and environment: Irrigation and drainage development." *Technical Note E.1.* World Bank. Washington, DC.

Denison, R. F., Bryant, D. C., and T.E., Kearney. (2004). "Crop yield over the first nine years of LTRAS a long-term comparison of field crop system in a Mediterranean climate." *Field crops Res.,* 86:267-277.

De Pascale, S., and Barbieri, G. (1997). "Effects of soil salinity and top removal on growth and yield of broadbean as a green vegetable." *Scientia Horticulturae,* 71: 147-165.

De Vos, J. A., Raats, P. A. C., and Feddes, R. A. (2002). "Chloride transport in a recently reclaimed Dutch polder." *Journal of Hydrology,* 257: 59-77.

De Wit, C. T., (1958). "Transpiration and crop yields." Institute of Biological and Chemical Research on Field Crops and Herbage, Wageningen, The Netherlands, Verse-Landvouwk, onderz. No. 64, 6-S, Gravenhage.

Dierckx, J., Belmans, C., and Pauwels, P. (1986). "SWATRER, a computer model package for modelling the field water balance" Reference manual. Soil and Water Engineering Lab., K. U. Leuven, Belgium.

Dingkuhn, M. and Le Gal, P-Y. (1996). "Effect of drainage date on yield and dry matter partitioning in irrigation rice." *Field Crop Research*, 46: 117-126.

Dirksen, C., Kool, J. B., and Van Genuchten, M. Th. (1993). HYSWASOR: simulation model of hysteretic water and solute transport in the root zone. In Rosso, D., Dagan, G., editors, *Water flow and solute transport in soils*, Pages 99-122. Springer, Berlin.

D'haeze, D., Deckers, J., Raes, D., An Phong, T., and Chanh, N. D. M. (2003). "Over-irrigation of *Coffea canephora* in the Central Highlands of Vietnam revisited simulation of soil moisture dynamics in Rhodic Ferralsols." *Agric. Water Management,* 63: 185-202.

Doorenbos, J., and Kassam, A. (1979). "Yield response to water" FAO Irrigation and Drainage Paper No. 33, Food and Agriculture Organisation, United Nations, Rome.

Doorenbos, J., and Pruitt, W. O. (1977). "Crop Water Requirements" Irrigation and Drainage Paper No. 24, Food and Agriculture Organisation, Rome, Italy.

Droogers, P., and Kite, G. (2001). "Simulation modelling at different scales to evaluate the productivity of water." *Phys. Chem. Earth,* 26: 877-880.

Droogers, P., Bastiaanssen, W. G. M., Beyazgul, M., Kayam, Y., Kite, G. W., and Murray-Rust, H. (2000). "Distributed agro-hydrological modelling of an irrigation system in western Turkey." *Agric. Water Management*, 43: 183-202.

Droogers, P., and Torabi, M. (2002). " Field scale scenarios for water and salinity management by simulation modelling." Research Report 12. Iranian Agricultural

Engineering Research Institute (IAERI), Karaj, Iran, International Water Management Institute (IWMI), Colombo, Sri Lanka.

Ducheyne, S., Schadeck, L., Vanongeval, L., Vandendriessche, H., Feyer, J. (2001). "Assessment of the parameters of a mechanistic soil-crop-nitrogen simulation model using historic data of experimental field sites in Belgium." *Agric. Water Management*, 51: 53-78.

EC (European Commission); "Water Resources Management and Agricultural Production (WRMAP)"; Formulation & Analysis of Regional Strategies on Land & Water Resources, *Annual Report,* July 1997.

Elmaloglou, S., and Malamos, N. (2000). "Simulation of soil moisture content of a prairie field with SWAP93." *Agric. Water Management,* 43: 139-149.

Espino, A., Mallants, D., Vanclooster, J., and Feyen, J. (1995). "Cautionary notes on the use of pedotransfer functions for estimating soil hydraulics properties." *Agric. Water Management,* 29: 235-253.

Fabeiro, C., Martin de Santa Olalla, F., and de Juan, J. A. (2001). "Yield and size of deficit irrigated potatoes." *Agric. Water Management*, 48: 255-266.

FAO, UNISCO. "Irrigation, Drainage, and salinity." An International source book. London, Hutchinson and CO. Ltd, 1973.

FAO, Land and Water Resources Development Division. Report on the Expert Meeting on crop water productivity. "Findings, recommendations and proposed follow-up." Rome, Italy, 2003,
http://www.fao.org/ag/agl/aglw/cropwater/finding.stm

Feddes, R. A., Kowalik, P. J., and Zaradny, H. (1978). "Simulation of field water use and crop yield." Simulation Monographs. Pudoc, Wageningen.

Fernandez, J. E., Slawinski, C., Moreno, F., Walczak, R. T., and Vanclooster, N. (2002). "Simulation the fate of water in a soil-crop system of a semi-arid Mediterranean area with the WAVE 2.1 and the EURO-ACCESS-II models." *Agric. Water Management*, 1738:1-17.

Flowers, T. J., Ragab, R., Malash, N., Abdel Gawad, G., Cuartero, J., and Arslan, A. (2005). "Sustainable strategies for irrigation in salt-prone Mediterranean: SALTMED." *Agric. Water Management,* 78: 3-14.

Gardner, W. (1958). "Some steady state solutions of the unsaturated moisture flow equation with application to evaporation from a water table." *Soil Sci.,* 85: 228-232.

Gavilan, P., Lorite, I. J., Tornero, S., and Berengena, J. (2006). "Regional calibration of Hargreaves equation for estimating reference ET in a semi-arid environment." *Agric. Water Management,* 81:257-261.

George, B. A., Shende, S. A., and Raghuwanshi, N. S. (2000). "Development and testing of an irrigation scheduling model." *Agric. Water Management*, 46: 121-136.

Gilham, R., W., Klute, A., and Herrmann. (1976). "Hydraulic properties of a porous medium. Measurements and empirical representations. *Soil Sci. Soc. of Am. J.,* 40: 203-207.

Gupta V. K., and Sorooshian, S. (1998). "Toward improved calibration of hydrologic models: Multiple and noncommensurable measures of information." *Water Resour. Res.,* 34(4): 751-763.

Hall, W. A., and Butcher, W. (1968). "Optimal timing of irrigation." *Irrigation and Drainage Engineering*, ASCE, 94(IR2): 267-275.

Hanks, R. J. (1974). "Model for predicting plant yield as influenced by water use." *Journal of Agronomy*, 66: 660-665.

Hargreaves, G. L., Hargreaves, G. H., and Riley, J. P. (1985). "Agricultural benefits for the Senegal river basin." *Irrigation and Drainage Engineering*, ASCE, 111(3): 265-275.

Hiler, E. A., and Clark, N. (1971). "Stress day index to characterize effect of water stress on crop yields." *Trans. of the ASAE.,* 14: 757-761.

Hill, R. W. (1991). Irrigation scheduling, ASA-CSSA-CSSA-SSSA., Madison, Wisconsin, U.S.A.

Homaee, M. (1999). *Root water uptake under non-uniform transient salinity and water stress*. Proefschrift Landbouwuniversiteit, Wageningen, The Netherlands.

Homaee, M., Feddes, R. A., and Dirksen, C. (2002a). "Simulation of root water uptake. II Non-uniform transient water stress using different reduction functions." *Agric. Water Management*, 57 (2): 111-126.

Homaee, M., Feddes, R. A., and Dirksen, C. (2002b). "Simulation of root water uptake. III Non-uniform transient combined salinity and water stress." *Agric. Water Management*, 57: 127-144.

Howell, T. A., and Hiler, E. A. (1975). "Optimisation of water use efficiency under high frequency irrigation –I. Evapotranspiration and yield relationship." *Trans. of the ASAE.*, 18:873-878.

HRW World Atlas, (http://www.go.hrw.com/atlas/norm_htm/kazakstn.htm).

Hussain, G., Al-Jaloud, A. A., Al-Shammary, S. A., Karimulla, S., and Al-Aswad, S. O. (1997). "Effect of saline irrigation on germination and growth parameters of barley (*Hordeum vulgare* L.)." *Agric. Water Management,* 34: 125-135.

Hutmacher, R. B., Ayars, J. E., Vail, S. S., Bravo, A. D., Dettinger, D., and Schoneman, R. A. (1996). "Uptake of shallow groundwater by cotton: growth stage, groundwater salinity effects in column lysimeter." *Agric. Water Management,* 31: 205-223.

Ines, A. V. M., Droogers, P., Makin, I. W., and Das Gupta, A. (2001). "Crop growth and soil water balance modelling to explore water management options. IWMI Working Paper No 22. Colombo, Sri Lanka: International Water Management Institute.

Israelsen, O. W., and Hansen, V. E. (1962). *Irrigation Principles and Practices.* John Wiley and Sons Inc., New York, U.S.A.

Jamieson, P. D., Porter, J. R., Goudriaan, J., Ritchie, J. T., van Keulen, H., and Stol, W. (1998). "A comparison of the models AFRCWHEAT2, CERES-Wheat, Sirius, SUCROS2 and SWHEAT with measurements from wheat grown under drought." *Field Crop Research,* 55: 23-44

Jensen, M. E. (1968). "Water consumption by agriculture plants". In Kozlowski, T., editor, *Water deficit and plant growth,* Volume 2, pages 1-22. Academic press, New York.

Joshi, M. B., Murthy, J. S. R., and Shah M. M. (1995). "CROSOWAT: A decision tool for irrigation schedule" *Agric. Water Management*, 27:203-223.

Kaledhonkar, M. J., Tyagi, N. K., Van Der Zee, S. E. A. T. M. (2001). "Solute transport modelling in soil for irrigating field experiments with alkali water." *Agric. Water Management,* 51: 153-171.

Kang, S., Zhang, L., Liang, Y., Hu, X., Cai, H., and Gu, Binjie. (2001). "Effects of limited irrigation on yield and water use efficiency of winter wheat in the Loess Plateau of China." *Agric. Water Management*, 1715:1-15.

Kang, S., Zhang, L., Liang, Y., and Dawes, W. (2003). "Simulation of winter wheat yield and water use efficiency in the Loess Plateau of China using WAVES." *Agricultural Systems,* 78: 355-367.

Kashyap, P. S., and Panda, P. K. (2001). "Evaluation of evapotranspiration estimation methods and development of crop coefficient for potato crop in a sub-humid region." *Agric. Water Management,* 50: 9-25.

Katerji, N., van Hoorn, J. W., Hamdy, A., and Mastrorilli, M. (2000). "Salt tolerance classification of crops according to soil salinity and to water stress index." *Agric. Water Management,* 43: 99-109.

Katerji, N., van Hoorn, J. W., Hamdy, A., Mastrorilli, M., Oweis T., and Erskine, W. (2001). "Response of two varieties of lentil to soil salinity." *Agric. Water Management,* 47: 179-190.

Khan, S., Tariq, R., Yuanlai, C., and Blackwell, J. (2006). "Can irrigation be sustainable." *Agric. Water Management*, 80: 87-99.

Khosla, B. K., and Gupta, R. K. (1997). "Response of wheat to saline irrigation and drainage." *Agric. Water Management,* 32: 285-291.

Kim, K. D., and Heo, J. (2002). "Comparative study of flood quantiles estimation by nonparametric models." *Journal of Hydrology,* 260: 176-193.

Kite, G., and Droogers, P. (2000a). " Integrated basin modelling." Research Report 43. Colombo, Sri Lanka: International Water Management Institute (IWMI).

Kite, G. W., and Droogers, P. (2000b). "Comparing evapotranspiration estimates from Satellite, Hydrological models, and Field data." *Journal of Hydrology*, 229: 3-18.

Konukcu, F., Gowing, J. W., and Rose, D. A. (2005). "Dry drainage: a sustainable solution to waterlogging and salinity problems in irrigated areas." *Agric. Water Management,* In Press.

Kroes, J. G., and Van Dam, J. C. (2003). "Reference Manual SWAP version 3.0.3." Alterra Green World Research. *Alterra Report 773*, Alterra, Wageningen, The Netherlands.

Lamsal, K., Paudyal, G. N., and Saeed, M. (1999). "Model for assessing impact of salinity on soil water availability and crop yield." *Agric. Water Management*, 41: 47-70.

Legates, D. R., and McCabe, G. J. (1999). "Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation." *Water Resour. Res.,* 35(1): 233-241.

Loague, K., and Green, R. E. (1991). "Statistical and graphical methods for evaluating solute transport models: Overview and applications." *Journal of contaminant Hydrology,* 7:51-73.

Maas, E. V., and Hoffman, G. J. (1977). "Crop salt tolerance: current assessment." *Irrigation and Drainage Engineering*, ASCE, 103(IR2): 115-134.

Martin, D. L., Stegman, E. C., and Fereres, E. (1992). Irrigation scheduling principles. In Hoffman, G. J., Howell, T. A., and Solomon, K. H., Editors, *Management of farm irrigation systems,* 2ND Edition, American Society of Agricultural Engineers, St. Joseph, MI, U.S.A.

Martin, D. L., Watts, D. G., and Gilley, J. R. (1984). "Model and production function for irrigation management." *Irrigation and Drainage Engineering*, ASCE, 110, 149-164.

Mastrorilli, M., Katerji, N., and Rana, G. (1999). "Productivity and water use efficiency of sweet sorghum as affected by soil water deficit occurring at different vegetative growth stages" *European Journal of Agronomy*, 11: 207-215.

Mathew, E. K., Panda, R. K., and Nair, M. (2001). "Influence of subsurface drainage on crop production and soil quality in a low-lying acid sulphate soil." *Agric. Water Management,* 47: 191-209.

McKeering, L., Foley, J., and Raine, S. (2004). "Evaluating the potential root zone drying (PRD) on clay soils in commercial cotton production systems." Cooperative Research Centre for Irrigation Futures, National Centre of Engineering in Agriculture (NCEA), The University of Southern Queensland (USQ), Toowoomba, Australia.

MDH Engineering Solution Corp. (2003). "Evaluation of computer models for predicting the fate and transport of salt in soil and groundwater." Science and Standards Branch, Alberta Environment, Edmonton, Alberta, Canada.

Meiresonne, L., Nadezhdin, N., Cermak, J., Van Slycken, J., and Ceulemans, R. (1999). "Measured sap flow and simulated transpiration from a poplar stand in Flanders (Belgium)." *Agric. and Forest Meteorology,* 96: 165-179.

Meiresonne, L., Sampson, D.A., Kowalski, A. S., Janssens, I. A., Nadezhdina, N., Cermak, J., Van Slycken, J., and Ceulemans, R. (2003). "Water flux estimates from a Belgian Scots pine stand: a comparison of different approaches." *Journal of Hydrology,* 270: 230-252.

Minhas, B. S., Parikh, K. S. and Srinivasan, T. N. (1974). "Toward the structure of a production function for wheat yields with dated inputs of irrigation water." *Water Resour. Res.*, 10(3): 383-393.

Minhas, P. S. (1996). "Saline water management for irrigation in India". *Agric. Water Management*, 30: 1-24.

Mogensen, V. O., Jensen, H. E., and Abdur Rab. (1985). "Grain yield, yield components, drought sensitivity and water use efficiency of spring wheat subjected to water stress at various growth stages." *Irrigation Science*, 6: 131-140.

Monteith, J. L. (1981). "Evaporation and surface temperature." *Q. J. R. Meteorol. Soc.,* 107: 1-27.

Montesinos, P., Camacho, E., and Alvarez, S. (2001) "Seasonal furrow irrigation model with genetic algorithms (OPTIMEC)." *Agric. Water Management*, 52:1-16.

Motovilov, Yu. G., Gottschalk, L., England, K., and Rodhe, A. (1999). "Validation of a distributed hydrological model against spatial observations." *Agric. Forest. Meteorol,* 98-99:257-277.

Mott MacDonald. (1999). Water Resources Management and Land Improvement Project (WRMLIP), *Inception Report,* Govt. of Kazakhstan.

Mott MacDonald. (2000a). Water Resources and Land Improvement Project (WRMLIP), *Working Paper No. 11a*: Review of Drainage Needs. Govt. of Kazakhstan.

Mott MacDonald. (2000b). Water Resources and Land Improvement Project (WRMLIP), *Working Paper No. 11b*: Status Report, Govt. of Kazakhstan.

Mott MacDonald. (2002). Water Resources and Land Improvement Project (WRMLIP), *Working Paper No. 22*: Preliminary Evaluation of Pilot Farm Data and WAVE Modelling. Govt. of Kazakhstan.

Mott MacDonald. (2003a). Water Resources and Land Improvement Project (WRMLIP), Scientific Report on Organisation Works and Field Investigation on Pilot Areas (2000-2002). Govt. of Kazakhstan.

Mott MacDonald. (2003b). Water Resources and Land Improvement Project (WRMLIP), *Working Paper No. 27*: Soil Monitoring Programme Results. Govt. of Kazakhstan.

Mott MacDonald. (2003c). Water Resources and Land Improvement Project (WRMLIP), *Working Paper No. 29*: WAVE Set-up, Calibration and Prediction. Govt. of Kazakhstan.

Mott MacDonald. (2003d). Water Resources and Land Improvement Project (WRMLIP), WRMLLLIP_WAVE model users manual, Govt. of Kazakhstan.

Mott MacDonald. (2004). Water Resources and Land Improvement Project (WRMLIP), *Working Paper No. 30*: Modelling Synthesis. Govt. of Kazakhstan.

Mualem, Y. (1976). "A new model for predicting the hydraulic conductivity of unsaturated porous media." *Water Resour. Res.*, 12(3): 513-522.

Pagliai, M., Marsili, A., Servadio, P., Vignozzi, N. and Pellegrini, S. (2003). "Change in some physical properties of a clay soil in central Italy following the passage of rubber tracked and wheeled tractors of medium power." *Soil Till. Res.*, 73: 119 – 129.

Pang, L., Close, M. E., Watt, P. C., and Vincent, K. W. (2000). "Simulation of Picloram, atrazine, and simazine leaching through two New Zealand soils and into groundwater using HYDRUS-2D." *Contaminant Hydrology,* 44: 19-46.

Perez, P., Ardlie, N., Kuneepong, P., Dietrich, C., and Merritt, W. S. (2002). "CATCHCROP: modelling crop yield and water demand for integrated catchment assessment in Northern Thailand." *Environmental Modelling & Software*, 17: 251-259.

Persicani, D. (1996). "Pesticide leaching into field soils: sensitivity analysis of four mathematical models." *Ecological Modelling,* 84: 265-280.

Querner, E. P., Morabito, J. A., Manzanera, M., Pazos, J.A., Ciancaglini, N. C., and Menenti, M. (1997). "The use of hydrological models in the irrigation areas of Mendoza, Argentina." *Agric. Water Management,* 35: 11-28.

Qureshi, S. A., Madramootoo, C. A., and Dodds, G. T. (2002). "Evaluation of irrigation schemes for sugarcane in Sindh, Pakistan, using SWAP93." *Agric. Water Management,* 54: 37-48.

Ragab, R. (2002). "A holistic generic integrated approach for irrigation, crop and field management: the SALTMED model." *Environmental Modelling & Software,* 17:345-361.

Ragab, R., Malash, N., Abdel Gawad, G., Arslan, A., and Ghaibeh, A. (2003). "SALTMED model structure, calibration and validation using field data from Egypt and Syria. International workshop on sustainable strategies for irrigation in salt-prone Mediterranean region: a system approach." Cairo, Egypt, 8-10 December 2003. http://www.nerc-wallingford.ac.uk/research/cairoworkshop/Papers/Ragab.pdf

Ragab, R., Malash, N., Abdel Gawad, G., Arslan, A., and Ghaibeh, A. (2005). "A holistic generic integrated approach for irrigation, crop and field management: 2. the SALTMED model validation using field data of five growing seasons from Egypt and Syria." *Agric. Water Management,* 78: 89-107.

Raghuwanshi, N. S., and Wallender, W. W. (1998). "Optimisation of furrow irrigation schedules, designs, and net return to water." *Agric. Water Management,* 35:209-226.

Rao, N. H., Sarma, P. B., and Chander, S. (1988). "A simple dated water production function for use in irrigated agriculture." *Agric Water Management*, 13: 25-32.

Rasul, G., and Thapa G. B. (2004). "Sustainability of ecological and conventional agricultural systems in Bangladesh: an assessment based on environmental, economic and social perspectives." *Agricultural Systems*, 79:327-351.

Rhoades, J. D., Kandiah, A., Mashali, A. M. (1992). "The use of saline waters for crop production." FAO Irrigation and Drainage Paper No. 48, Rome.

Rinaldi, M. (2001). "Application of EPIC model for irrigation scheduling of sunflower in Southern Italy." *Agric. Water Management,* 49: 185-196.

Sampson, D. A., Janssens, I. A., Ceulemans R. (2001). "Simulated soil CO_2 efflux and net ecosystem exchange in a 70-year old Belgian Scots pine stand using the process model SECRETS." *Annual of Forest Science,* 58: 31-44.

Saranga, Y., Flash, I., Paterson, A., and Yakir, D. (1999). "Carbon isotope ratio in cotton varies with growth stage and plant organ." *Plant Science*, 142:47-56.

Sarwar, A., Bastiaanssen, W. G. M., and Feddes R. A. (2001). "Irrigation water distribution and long-term effects on crop and environment." *Agric. Water Management,* 50: 125-140.

Schultz, B. (2001). "Irrigation, drainage and flood protection in a rapidly changing world." *Irrigation and Drainage,* 50: 261-277.

Sezen, S. M., and Yazar, A. (2006) "Wheat yield response to line-source sprinkler irrigation in the arid Southeast Anatolia region of Turkey." *Agric. Water Management,* 81: 59-76.

Sezen, S. M., Yazar, A., and Eker, S. (2006). "Effect of drip irrigation regimes on yield and quality of field grown bell pepper." *Agric. Water Management,* 81: 115-131.

Sharma, D. P., and Rao. (1998). "Strategy for long term use of saline drainage water for irrigation in semi-arid region." *Soil & Tillage Research,* 48: 287-295.

Simunek, J., Suarez, D. L., and Sejna, M. (1996). "The UNSATCHEM Software package for simulating dimensional variably saturated water flow, heat transport, carbon dioxide production and transport, and solute transport with major ion equilibrium and kinetic chemistry." Version 2.0. *Research Report No. 141*, USDA, ARS, U.S. Salinity Laboratory, Riverside, California.

Simunek, J., Huang, K., and van Genuchten, M. Th. (1999). "The HYDRUS-2D software package for simulating the two-dimensional movement of water, heat and multiple solutes in variably saturated media." Version 2.0, IGWMC-TPS-53, International Ground Water Modelling Centre, Colorado School of Mines, Golden, Colorado.

Simunek, J., van Genuchten, M. Th., Gribb, M. M., and Hopmans, J. W. (1998). "Parameter estimation of unsaturated soil hydraulic properties from transient flow processes" *Soil & Tillage Research,* 47: 27-36.

Singh, R. (2004). "Simulations on direct and cyclic use of saline waters for sustaining cotton-wheat in a semi-arid area of north-west India." *Agric. Water Management,* 66: 153-162.

Slavich, P. G., Hatton, T. J., and Dawes, W. R. (1998). "The canopy growth and transpiration model of WAVES: Technical description and evaluation." *Technical Report No 3/98*, CSIRO Land and Water, Canberra, Australia.

Smedema, L. K. (2002). "Land drainage: An instrument for agriculture and rural development." International Commission for Irrigation and Drainage (ICID).

Smets, S. M. P., Kuper, M. Van Dam, J. C., and Feddes, R. A. (1997). "Salinisation and Crop transpiration of irrigated fields in Pakistan's Punjab." *Agric. Water Management,* 35:43-60.

Smith, M., Allen R. G., Monteith, J. L., Pereira, L. S., Perrier, A., and Pruitt, W. O. (1992). Report on the Expert Consultation on procedures for revision of FAO Guidelines for prediction of crop water requirements. Land and Water Resources UN-FAO, Rome, Italy.

Smith, M. (1992). "CROPWAT a computer program for irrigation planning and management" FAO Irrigation and Drainage Paper No. 46, Food and Agriculture Organisation, United Nations, Rome, Italy.

Spitters, C. J. T., Van Keulen, H., and Van Kraailingen D. W. G. (1988). A simple but universal crop growth simulation model, SUCROS87. In Rabbinge, R., Van Laar, H., and Ward, S., Editors, *Simulation and systems management in crop protection.* Simulation monographs, PUDOC, Wageningen, The Netherlands.

Stamford, N. P., Silva, A. J. N., Freitas, A. D. S., and Araujo Filho, J. T. (2002). "Effect of sulphur inoculated with *Thiobacillus* on soil salinity and growth of tropical tree legumes." *Bioresource Technology,* 81:53-59.

Stewart, J. L., Hagan, R. M., and Pruitt, W. O. (1976). " Production function and predicted irrigation programmes for principal crops as required for water resources planning and increased water use efficiency." Final report, US Dept. of Interior, Washington DC.

Suarez, D. L. (2002). "Evaluation of management practices for use of low quality waters for irrigation: model simulations." *Proc., Meetings of the int. Union of Soil Scientists*, August 14-21, 2002, Bangkok, Thailand, Symposium No. 34, 1096: 1-8

Sudar, R. A., Saxton, K. E., and Spomer, R. G. (1981). "A predictive model of water stress in corn and soybean." *Trans. of the ASAE.*, 24: 97-102.

Szabolcs, I. (1994). "Soils and salinisation." In Pessarakli, M., editor, *Handbook of plant and crop stress*, Marcel Dekker, New York

Tsakiris, G. P. (1982). "A method for applying crop sensitivity factors in irrigation scheduling." *Agric. Water management*, 5: 335-343.

Tyagi, N. K. (1986). "Optimum water management strategies for salinity control." *Irrigation and Drainage*, 112 (2): 81-97.

United Nation (UN), Department of Economic and Social Affairs, Population Division, 2005.
http://esa.un.org/unpp/p2k0data.asp

Utset, A., and Borroto, M. (2001). "A modelling-GIS approach for assessing irrigation effect on soil salinisation under global warming conditions." *Agric. Water Management,* 50: 53-63.

Vanclooster, M., Viaene, P., Diels., J., and Christiaens K. (1994). "WAVE a mathematical model for simulating water and agrochemicals in the soil and vadose environment." Inistitute for Land and Water Management, Katholieke University of Leuven, Leuven, Belgium.

Vanclooster, M., Viaene, P., Diels, J., and Feyen, J. (1995). "A deterministic evaluation analysis applied to an integrated soil-crop-model." *Ecological Modelling*, 81: 183-195.

Vanclooster, M., Boesten, J. J. T. I., Trevisan, M., Brown, C. D., Capri, E., Eklo, O. M., Gottesburen, B, Gouy, V., van der Linden, A. M. A. (2000a). " A European test of pesticide-leaching models: methodology and major recommendations." *Agric. Water Management*, 44: 1-19.

Vanclooster, M., Ducheyne, S., Dust, M., Vereecken, H. (2000b). "Evaluation of pesticide dynamic of the WAVE-model." *Agric. Water Management*, 44: 371-388.

Van Dam, J. C., Huygen, J., Wesseling, J. G., Feddes, R. A., Kabat, P., van Waslum, P. E. V., Groenendjik, P., and Van Diepen, C. A. (1997). "Theory of SWAP version 2.0: Simulation of water flow and plant growth in the Soil-Water-Atmosphere-Plant environment." *Technical Document 45*, Wageningen Agricultural University, Wageningen, The Netherlands.

Van Dam, J. C. (2000). *"Field-scale water flow and solute transport: SWAP model concepts, parameter estimation and case studies."* PhD thesis, Wageningen University, Wageningen, The Netherlands.

van Genuchten, M. Th. (1980). "A close-form equation for predicting the hydraulic conductivity of soil." *Soil Sci. Soc. Am. J.,* 44:892-898.

Van Genuchten, M. Th. (1983). "Analysing crop salt tolerance data: Model description and user's manual." USDA-ARS-USSI Research Report No 120.

van Genuchten, M. T. (1987). "A numerical model for water and solute movement in and below the root zone." *Research Report No. 121,* USDA, ARS, U. S. Salinity Laboratory, Riverside, California.

van Keulen, H., Penning de Vries, F. W. T., and Drees. (1982). A summary model for crop growth. In Penning de Varies, F. W. T., and van Laar, H., editors, *Simulation of plant growth and crop production,* pages 87-98. Simulation Monographs, PUDOC, Wageningen, The Netherlands.

Vazquez, R. F., and Feyen, J. (2003). "Effect of potential evapotranspiration estimates on effective parameters and performance of the MIKE SHE-code applied to a medium-size catchment." *Journal of Hydrology,* 270: 309-327.

Verhagen, A., Booltink, H. W. G., and Bouma, J. (1995). "Site-specific management: Balancing production and environmental requirements at farm level." *Agricultural Systems,* 49: 369-384.

Vulkan-Levy, R., Ravina, I., Mantell, A., and Frenkel, H. (1998). " Effect of water supply and salinity on pima cotton." *Agric. Water Management,* 37: 121-132.

Wagenet, R. J., and Hutson, J. L. (1989). "LEACHM, a process based model of water and solute movement, transformations, plant uptake and chemical reactions in the unsaturated zone." Centre for Environmental Research, Cornell University, Ithaca, N. Y.

Wang, H., Zhang, L., Dawes W. R., and Liu, C. (2001). "Improving water use efficiency of irrigated crops in the North China plain-measurement and modelling." *Agric. Water Management*, 48: 151-167.

Wardlaw, R., and Barnes, J. (1996). "Improved irrigation system planning and management." Technical Report, Dept. of Civil & Environmental Engineering, Univ. of Edinburgh, UK.

White, N., and Zelazny, L. W. (1986). Charge properties in soil colloids. In Sparks, D. L., editor, *Soil physical chemistry,* CRC Press, BOCA Raten, Florida, U.S.A.

Wilcox, B. P., Rawls, W. J., Brakensiek, D. L., Write J. R. (1990). "Predicting runoff from Rangeland catchment: A comparison of two models." *Water Resour. Res.,* 26(10): 2401-2410.

WUFMAS. (1999). "Water Use and Farm Management Survey (WUFMAS)." Annual Report. Tacis Service DG 1A, European Commission, Brussels.

Xevi, E., Gilley, J., Feyen, J. (1996). "Comparative study of two crop yield simulation models." *Agric. Water Management,* 30:155-173.

Yazar, A., Metin Sezen, S., and Sesvern, S. (2001). "LEPA and trickle irrigation of cotton in the Southeast Anatolia project (GAP) area in Turkey." *Agric. Water Management*, 1714:1-15.

Yurtseven, E., Kesmez, G. D., and Unlukara, A. (2005). "The effect of water salinity and potassium level on yield, fruit quality and water consumption of a native central Anatolian tomato species." *Agric. Water Management,* 78: 128-135.

Zhang, L., Dawes, W. R., and Hatton, T. J. (1996). "Modelling hydrologic processes using a biophysically based model-application of WAVES to FIFE and HAPEX-MOBILHY." *Journal of Hydrology,* 185: 147-169.

Zhang, H., and Oweis, T. (1999). "Water-yield relations and optimal irrigation scheduling of wheat in the Mediterranean region." *Agric. Water Management,* 38:195-211.

Zhang, L., and Dawes, W.R. (1998). "WAVES an integrated energy and water balance model." *Technical Report No. 31/98*, CSIRO Land and Water, Canberra, Australia.

Zhang, L., Dawes, W. R., Slavich, P. G., Meyer, W. S., Thorburn, P. J., Smith, D. J., and Walker, G. R. (1999). "Growth and ground water uptake responses of lucerne to change in groundwater levels and salinity: lysimeter, isotope and modelling studies." *Agric. Water Management,* 39: 265-282.

Appendices

A. The Modified WAT_UPT.FOR Source Code

This appendix contains the source code of the subroutine in which the actual crop transpiration functions were modified by incorporating the affect of salinity on crop transpiration.

```
C#####################################################################################
C      IN   : DRZ, DT, DX, EPA_MIN_INTC, ILINR, ISUCR, NCS, NDAY, P0, P1,
C             P2H, P2L, P3, PH, RNAM, RT_DISTR, SIMPLANT, T, TB, TE, WC, X
C      OUT  : IRZ, RTEX
C      CALLS: CALC_WC, ROOT_SUCROS
C#####################################################################################
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      INCLUDE   'CONSTANT'
      INCLUDE   'GEN.COM'
      INCLUDE   'CLIM.COM'
      INCLUDE   'WAT.COM'
      INCLUDE   'SOL.COM'
      INCLUDE   'CROP_CHAR.COM'
      DIMENSION WCWP(KT_COMPS)

CPEV 496 NEW VARIABLES
CPEV 4/96  RTEX(i) = (ALPHA(i)*FR_POT_ET(i)*Tpot+rest)/DX
      DIMENSION ALPHA_RED(KT_COMPS)
      DIMENSION RTEX1(KT_COMPS)
      DIMENSION FR_POT_ET(KT_COMPS)
      INTEGER SP
      DOUBLE PRECISION REST
CPEV 4/96 END DECLARATION NEW VARIABLES


      IF (.NOT.SIMPLANT) RETURN
C     DETERMINE ROOT LENGTH
      IF (ISUCR)  DRZ(NDAY) =  ROOT_SUCROS()



CPEV 7/96  INTRODUCING CALC_DIM_ROOTS
CPEV CALCULATE THE COMPARTMENTS IRA AND IRZ
C     IRA =  COMPARTMENT FOR WHICH THE BOTTOM IS BELOW THE FIRST COMPARTMENT
C            IN WHICH THERE IS EXTRACTION
C     IRZ =  COMPARTMENT FOR WHICH THE LOWER BOUNDARY IS LESS OR EQUAL TO DRZ
C     RNA = DEPTH ABOVE WHICH ROOTS ARE INACTIVE

      IF( DINT(T)-T.EQ.0.D0) CALL CALC_DIM_ROOTS(IRA,IRZ,RNA)

CPEV 4/96 END OF CALCULATION OF IRA, IRZ AND RNA

CPEV 4/96 CALCULATION OF RTEX1
CPEV 4/96 1) CALCULATION OF FRACTIONS, FR_POT_ET

CPEV 7/96 INTRODUCING CALC_RT_DISTR
      IF( DINT(T)-T.EQ.0.D0) CALL CALC_RT_DISTR(FR_POT_ET)
```

```
CPEV 4/96 2) CALCULATION OF RTEX1(I)
      DO 50 I = 1,IRZ
         RTEX1(I) =   FR_POT_ET(I)* EPA_MIN_INTC/DX
50    CONTINUE
CPEV 4/96 END OF CALCULATION RTEX1(I)


CEPV 4/96 CALCULATION OF RTEX
C     IF ROOTS START EXTRACTING BELOW LOWEST COMPARTMENT (IRA > NCS)
      IF (IRA.GT.NCS) THEN
        DO 60 I = 1, NCS
          RTEX(i) = 0.D0
60      CONTINUE
      ELSE
CPEV    FOR COMPARTMENTS ABOVE IRA RTEX = 0, REST + SUM(RTEX(i), i= 1,IRZ-1)
        REST = 0
        DO 70 I = 1, IRA - 1
          REST = REST + RTEX1(I)
          RTEX(I) = 0.D0
70      CONTINUE



CPEV    CALCULATION OF ALPHA (reduction factor f(h))
        P2=P2H
        IF(EPA_MIN_INTC.LT.0.1D0) THEN
          P2=P2L
        ELSE
          IF(EPA_MIN_INTC.LT.0.5D0)
     $    P2=P2H+((0.5D0-EPA_MIN_INTC)/0.4D0)*(P2L-P2H)
        ENDIF
        DO 90 I=IRA,IRZ
          IF(PH(I).GT.P1) THEN
            IF (P0.GT.P1) THEN
              ALPHA_RED(I)=DMAX1((P0-PH(I))/(P0-P1),0.0D0)
            ELSE
              ALPHA_RED(I) = 0.D0
            ENDIF
          ENDIF
          IF(PH(I).LT.P2) THEN
            IF (PH(I).GT.P3) THEN
              IF (P3.LT.P2) THEN
                IF(ILINR) THEN
C                 LINEAR RELATIONSHIP
                  ALPHA_RED(I)=DMAX1((P3-PH(I))/(P3-P2),0.0D0)
                ELSE
                  ALPHA_RED(I)=10**((P2-PH(I))/P3)
                ENDIF
              ELSE
                ALPHA_RED(I) = 0.D0
              ENDIF
            ELSE
              ALPHA_RED(I) = 0.D0
            ENDIF
           ELSE
           ALPHA_RED(I) = 1.D0
          ENDIF
90      CONTINUE
C      MODIFIED 4/12/2002 TO INCLUDE THE EFFECT OF SALINITY ON CROP
C      TRANSPIRATION FOLLOWING THE APPROACH OUTLINED IN THE FAO
C      IRRIGATION AND DRAINAGE PAPER NO. 56 (Allen et al., 1998)

           IF (SIMSOL) THEN
            DO 91 I=1, IRZ
               DO 95 J=1,NPL
              SP=1
```

```
            SALT_CONC(I,SP)=(TCSOLO(I,SP)/(BULK_DENS(J)*1.0E6
     $                 *DX))*(1.0-KDS)*100.0
95            CONTINUE
91          CONTINUE
           ENDIF
C
          DO 92 I=1, IRZ
             ECE(I)=(1640.0*SALT_CONC(I,SP)+4.25)/100.0
92        CONTINUE
C
          DO 93 I=1,IRZ
             IF (ECE(I).GT.A_FACT) THEN
               SAL_RED(I)=1.0-B_FACT*(ECE(I)-A_FACT)
     $                  /(Y_RED_WATER(I)*100.0)
             ELSE
               SAL_RED(I)=1.0
             END IF
93        CONTINUE

C       ROOT EXTRACTION RATE IS ALSO LIMITED TO AVOID EXTRACTION BELOW
C       WILTING POINT (WCWP)
C       CALCULATION OF WATER CONTENT AT WILTING POINT
        DO 100 I = IRA, IRZ
          WCWP(I)=CALC_WC(P3,I)
100      CONTINUE

CPEV    CALCULATION OF RTEX(i) FROM RTEX1, ALPHA_RED AND REST
        DO 110 I = IRA, IRZ
          RTEX(I)= DMAX1(0.D0,
     $                 DMIN1(ALPHA_RED(I)*SAL_RED(I)*(RTEX1(I)+REST),
     $                       (WC(I)-WCWP(I))/DT) )
          REST = DMAX1(REST-RTEX(I) + RTEX1(I)-RTEX(I),0.D0)
110     CONTINUE

C       RTEX(I)= 0 FOR COMPARTMENTS BELOW THE ROOT ZONE
        DO 120 I = IRZ+1, NCS
          RTEX(I) = 0.D0
120     CONTINUE
      ENDIF

CPEV 4/96 END OF NEW CALCULATIONS
      RETURN
      END


      SUBROUTINE ETSPLIT
C##############################################################################
C     IN   : ETO, HARVEST_DATE,
C            IDVS, ISUCR, NDAY, PLANT_DATE, RLAI, SIMPLANT, T,
C     OUT  : AKC, DVS_ACT, EPA, EPA_MIN_INTC, ESA, EV_INTC, STOR
C     CALLS: DVS_SUCROS, RLAI_SUCROS
C##############################################################################
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      INCLUDE   'CONSTANT'
      INCLUDE   'GEN.COM'
      INCLUDE   'WAT.COM'
      INCLUDE   'CLIM.COM'
      DATA KC_NUM /1/


CPEV    CALCULATION OF KC FACTOR
      IF (IDVS) THEN
        DVS_ACT = DVS_SUCROS()
        IF (KC_NUM.EQ.1. AND. DVS_ACT.LE.DVS_KC(1)) THEN
          AKC = KC(KC_NUM)
        ELSE IF (KC_NUM.EQ.NR_OF_KC_VALUES. AND.
     $                    DVS_ACT.GE.DVS_KC(KC_NUM)) THEN
```

```
            AKC = KC(KC_NUM)
          ELSE
            IF (DVS_ACT.GT.DVS_KC(KC_NUM)) KC_NUM = KC_NUM + 1
            AKC = KC(KC_NUM - 1) +
     $            (KC(KC_NUM)      -     KC(KC_NUM-1)) *
     $            (DVS_ACT         - DVS_KC(KC_NUM-1))    /
     $            (DVS_KC(KC_NUM) - DVS_KC(KC_NUM-1))
          ENDIF
      ELSE
          IF (KC_NUM.EQ.1. AND. T.LE.(IDAY_KC(1))) THEN
            AKC = KC(KC_NUM)
          ELSE IF (KC_NUM.EQ.NR_OF_KC_VALUES. AND.
     $                  T.GE.(IDAY_KC(KC_NUM))) THEN
            AKC = KC(KC_NUM)
          ELSE
            IF (T.GT.(IDAY_KC(KC_NUM))) KC_NUM = KC_NUM + 1
            AKC = KC(KC_NUM - 1) +
     $            (KC(KC_NUM)      -     KC(KC_NUM-1)) *
     $            (T               - (IDAY_KC(KC_NUM-1))) /
     $            ((IDAY_KC(KC_NUM))-(IDAY_KC(KC_NUM-1)))
          ENDIF
      ENDIF

      IF(ISUCR) RLAI(NDAY) = RLAI_SUCROS()
CPEV      IF(.NOT.SIMPLANT) AKC = 1.0D0
      ET0A=AKC*ET0(NDAY)
      ESA= DEXP(-0.6D0* RLAI(NDAY))*ET0A
      EPA=ET0A-ESA
C     ACCOUNT FOR THE EVAPORATION OF INTERCEPTED WATER
      EV_INTC =  DMIN1 (STOR , EPA)
      EPA_MIN_INTC = EPA - EV_INTC
      STOR = STOR - EV_INTC
      END


      DOUBLE PRECISION FUNCTION CALC_WAT_DRZ(DAY)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      INCLUDE   'CONSTANT'
      INCLUDE   'WAT.COM'
      INTEGER DAY
      CALC_WAT_DRZ = DRZ(DAY)
      RETURN
      END


      DOUBLE PRECISION FUNCTION CALC_RTEX(NR_OF_COMP)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      INCLUDE   'CONSTANT'
      INCLUDE   'WAT.COM'
      CALC_RTEX = RTEX(NR_OF_COMP)
      RETURN
      END


      DOUBLE PRECISION FUNCTION CALC_WATREDUCTGROW ()
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      INCLUDE   'CONSTANT'
CMAR 6/12/1995
      INCLUDE   'GEN.COM'
      INCLUDE   'WAT.COM'

CPEV1/4/96
      IF (IDINT(T).LT.PLANT_DATE.OR.IDINT(T).GT.HARVEST_DATE) THEN
        CALC_WATREDUCTGROW=0.D0
        RETURN
```

```
      ENDIF
      IF (EPA.EQ.0.D0) THEN
        CALC_WATREDUCTGROW = 0.D0
      ELSE
CMAR 6/12/1995
         CALC_WATREDUCTGROW =  DMIN1(((TRANSP_ACT+EV_INTC)/EPA),1.D0)
      ENDIF
      END


      SUBROUTINE CALC_DIM_ROOTS(IRA,IRZ,RNA)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      INCLUDE   'CONSTANT'
      INCLUDE   'GEN.COM'
      INCLUDE   'WAT.COM'

C     IRA =  COMPARTMENT FOR WHICH THE BOTTOM IS BELOW THE FIRST COMPARTMENT
C            IN WHICH THERE IS EXTRACTION
C     IRZ =  COMPARTMENT FOR WHICH THE LOWER BOUNDARY IS LESS OR EQUAL TO DRZ
C     RNA = DEPTH ABOVE WHICH ROOTS ARE INACTIVE

CPEV INACTIVATION OF THE ROOTS NEAR THE SURFACE AFTER TB

      IF(T.GE.TB) THEN
C       NOTE THAT THE INACTIVE ROOTZONE CAN BE AT MOST THE COMPLETE
C       ROOT ZONE DEFINED BY DRZ
        IF (TE.EQ.TB) THEN
          RNA = DMAX1(RNAM,DRZ(NDAY))
        ELSE
          RNA= DMAX1(RNAM* DMIN1((T-TB)/(TE-TB),1.D0),DRZ(NDAY))
        ENDIF
      ELSE
        RNA=0.0
      ENDIF

      IRA = 1
10    IF((X(IRA)-DX/2.).GE.RNA)THEN
        IRA=IRA + 1
        IF (IRA.LE.NCS) GOTO 10
      ENDIF

      IRZ = IRA
      IF (IRA.LE.NCS) THEN
C       DETERMINE COMPARTMENT FOR WHICH THE LOWER BOUNDARY IS
C       LESS OR EQUAL TO DRZ (IRZ)
20      IF((X(IRZ)-DX/2.).GT.DRZ(NDAY))THEN
          IRZ = IRZ +1
          IF (IRZ .LE.NCS) GOTO 20
        ENDIF
      ENDIF
      IRZ = MIN(IRZ, NCS)
      RETURN
      END


      SUBROUTINE CALC_RT_DISTR(FRACTIONS)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      INCLUDE   'CONSTANT'
      INCLUDE   'GEN.COM'
      INCLUDE   'WAT.COM'
      DIMENSION FRACTIONS(*)

      CALL CALC_DIM_ROOTS(IRA,IRZ,RNA)
      SUM_OF_RT_DISTR = 0.D0
      IF (IRA.NE.IRZ) THEN
        SUM_OF_RT_DISTR = RT_DISTR(IRA)* (RNA - (X(IRA)-DX/2.))/DX
        DO 30 I = IRA+1,IRZ -1
         SUM_OF_RT_DISTR = SUM_OF_RT_DISTR + RT_DISTR(I)
```

```
30        CONTINUE
C         FOR LAST COMPARTMENT CORRECT FOR PARTIAL UPTAKE
          SUM_OF_RT_DISTR = SUM_OF_RT_DISTR+RT_DISTR(IRZ)*
     $                      ((DX/2.)+X(IRZ)-DRZ(NDAY))/DX
        ELSE
CPEV    ALL EXTRACTION FROM 1 COMPARTMENT (IRZ = IRA)
          SUM_OF_RT_DISTR = (RNA - DRZ(NDAY))/DX
        ENDIF

        IF (SUM_OF_RT_DISTR.GT.0.D0) THEN
          DO 35 I = 1, IRA-1
             FRACTIONS(I) = 0.D0
35        CONTINUE
          DO 40 I = IRA,IRZ
             FRACTIONS(I) = RT_DISTR(I)/SUM_OF_RT_DISTR
40        CONTINUE
C         FOR FIRST & LAST COMPARTMENT CORRECT FOR PARTIAL UPTAKE
          IF (IRA.NE.IRZ) THEN
           FRACTIONS(IRA) = (RT_DISTR(IRA)*(RNA - (X(IRA)-DX/2.))/DX)
     $           /SUM_OF_RT_DISTR
           FRACTIONS(IRZ) = (RT_DISTR(IRZ)*((DX/2.)+X(IRZ)-DRZ(NDAY))
     $                      /DX)
     $           /SUM_OF_RT_DISTR
          ELSE
CPEV       IRA = IRZ (ALL EXTRACTION FROM 1 COMPARTMENT)
           FRACTIONS(IRA) = 1.D0
          ENDIF
        ELSE
          DO 45 I = 1, IRZ
             FRACTIONS(I) = 0.D0
45        CONTINUE
        ENDIF
        RETURN
        END
```

B. The source code for the new subroutine CROP_CHAR.FOR

This appendix contains the source code of the new subroutine CROP_CHAR.FOR which developed to read the additional input data required by the new concepts incorporated.

```
      SUBROUTINE CROP_CHAR()
C  Subroutine to read crop data for yield reduction and reduction in water uptake
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      INCLUDE 'CROP_CHAR.COM'
      INTEGER STAGE_LENGTH(5)
      CHARACTER TITLE*64
C
      KDS=0.0
C
C Read cropping data
C
      OPEN(7,FILE="CROP_CHAR.DAT")
      READ(7,'(A)') TITLE
      READ(7,*) NUM_STAGES
      READ(7,*) (STAGE_LENGTH(I),I=1,NUM_STAGES)
      READ(7,*) (Y_RED_WATER(I),I=1,NUM_STAGES)
      READ(7,*) A_FACT,B_FACT
      WRITE(*,'(3(A,F7.2))') " A_FACT = ",A_FACT," B_FACT = ",
     $ B_FACT
      PAUSE
      READ(7,*) DAY_PLNT, MONTH_PLNT, YEAR_PLNT
      WRITE(*,'(A)') " Crop-char READ"
      CLOSE(7)
C
      END SUBROUTINE
```

C. Irrigation and Drainage Scenarios

The following tables show the amount of water applied and time of application as well as the annual drainage, drainage timing and drainage rate for the irrigation and drainage scenarios that were considered.

Possible irrigation and leaching scenarios

Annual Application	Scenario	15/01	30/01	15/02	28/02	15/03	30/03	15/05	31/05	15/06	30/06	15/07	30/07	15/08	30/08	15/09
400 *mm*	A		100	100	100							50		50		
400 *mm*	B		100	100								100		100		
600 *mm*	C		100	100	100					100		100		100		
800 *mm*	D	100	100	100	100					100	100	100		100		
800 *mm*	E		100	100	100					100	100	100	100	100		
800 *mm*	F		100	100						100	100	100	100	100	100	
1000 *mm*	G	100	100	100	100					100	100	100	100	100	100	
1000 *mm*	H		100	100	100				100	100	100	100	100	100	100	
1200 *mm*	I	100	100	100	100				100	100	100	100	100	100	100	100
1200 *mm*	J		100	100	100			100	100	100	100	100	100	100	100	100

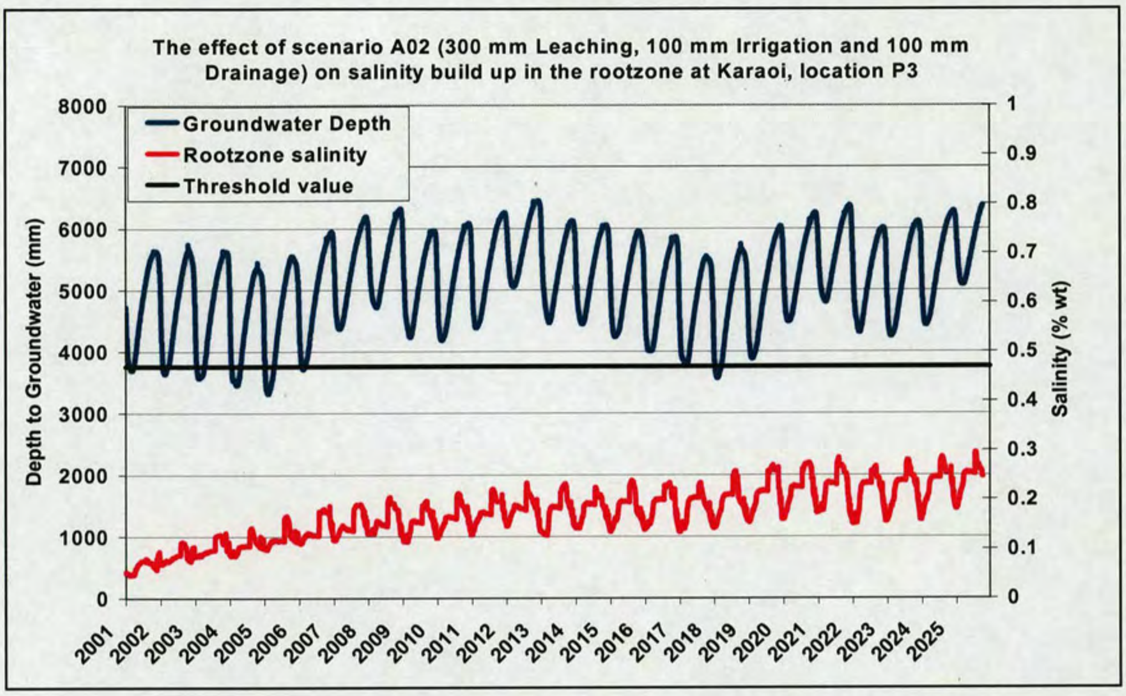
Possible drainage scenarios – flux rates in mm/day

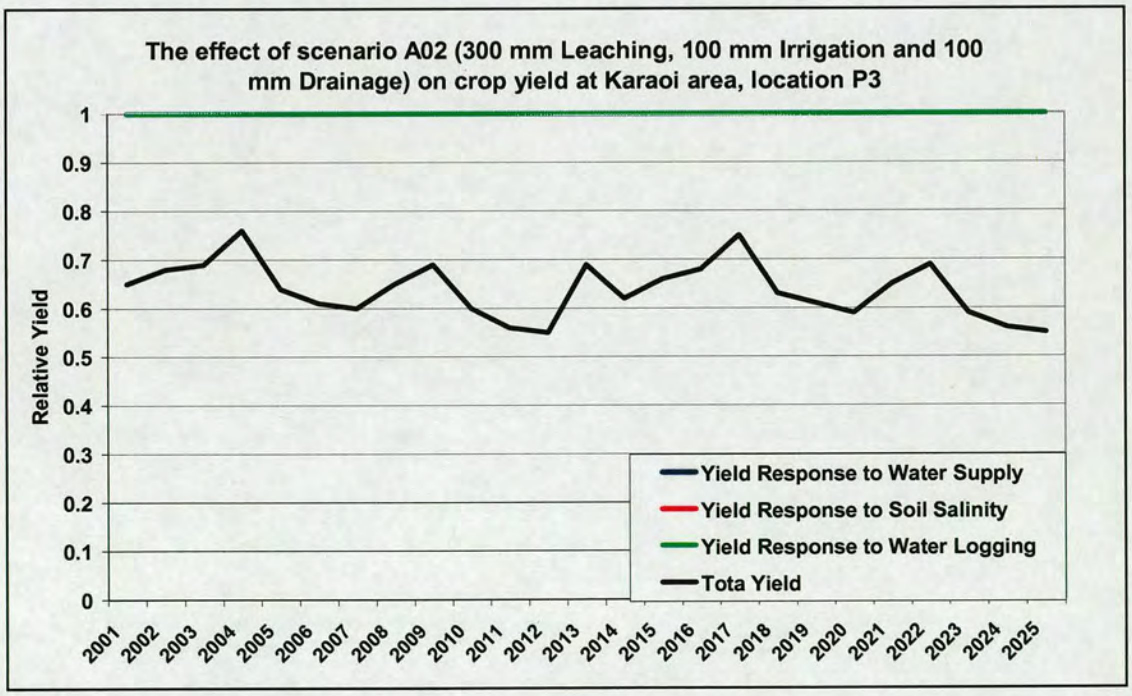
Annual Drainage	Scenario	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	1	0	0	0	0	0	0	0	0	0	0	0	0
100	2	-0.274	-0.274	-0.274	-0.274	-0.274	-0.274	-0.274	-0.274	-0.274	-0.274	-0.274	-0.274
100	3	-0.662	-0.662	-0.662	0	0	0	0	0	0	0	-0.662	-0.662
200	4	-0.548	-0.548	-0.548	-0.548	-0.548	-0.548	-0.548	-0.548	-0.548	-0.548	-0.548	-0.548
200	5	-1.099	-1.099	-1.099	0	0	0	0	0	0	-1.099	-1.099	-1.099
200	6	-1.325	-1.325	-1.325	0	0	0	0	0	0	0	-1.325	-1.325
300	7	-0.822	-0.822	-0.822	-0.822	-0.822	-0.822	-0.822	-0.822	-0.822	-0.822	-0.822	-0.822
300	8	-1.648	-1.648	-1.648	0	0	0	0	0	0	-1.648	-1.648	-1.648
300	9	-1.987	-1.987	-1.987	0	0	0	0	0	0	0	-1.987	-1.987
400	10	-1.096	-1.096	-1.096	-1.096	-1.096	-1.096	-1.096	-1.096	-1.096	-1.096	-1.096	-1.096
400	11	-2.198	-2.198	-2.198	0	0	0	0	0	0	-2.198	-2.198	-2.198
400	12	-2.649	-2.649	-2.649	0	0	0	0	0	0	0	-2.649	-2.649
500	13	-1.370	-1.370	-1.370	-1.370	-1.370	-1.370	-1.370	-1.370	-1.370	-1.370	-1.370	-1.370
500	14	-2.747	-2.747	-2.747	0	0	0	0	0	0	-2.747	-2.747	-2.747
500	15	-3.311	-3.311	-3.311	0	0	0	0	0	0	0	-3.311	-3.311
550	16	-1.507	-1.507	-1.507	-1.507	-1.507	-1.507	-1.507	-1.507	-1.507	-1.507	-1.507	-1.507
550	17	-3.022	-3.022	-3.022	0	0	0	0	0	0	-3.022	-3.022	-3.022
550	18	-3.642	-3.642	-3.642	0	0	0	0	0	0	0	-3.642	-3.642
600	19	-1.644	-1.644	-1.644	-1.644	-1.644	-1.644	1.644	-1.644	-1.644	-1.644	-1.644	-1.644
600	20	-3.297	-3.297	3.297	0	0	0	0	0	0	-3.297	-3.297	-3.297
600	21	-3.974	-3.974	-3.974	0	0	0	0	0	0	0	-3.974	-3.974

D. The WAVE Model Results

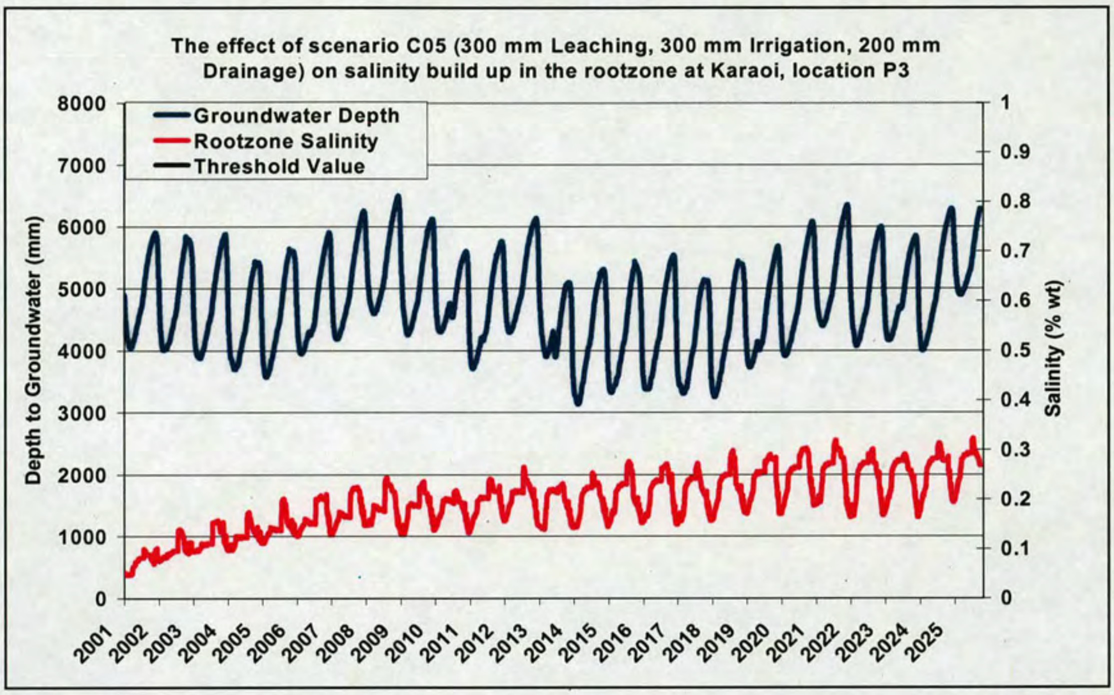
The following figures show the WAVE model results for some selected locations. Results are presented in terms of watertable depth and rootzone salinity, as well as in terms of crop yield response to the combined effect of water supply, salinity and waterlogging.

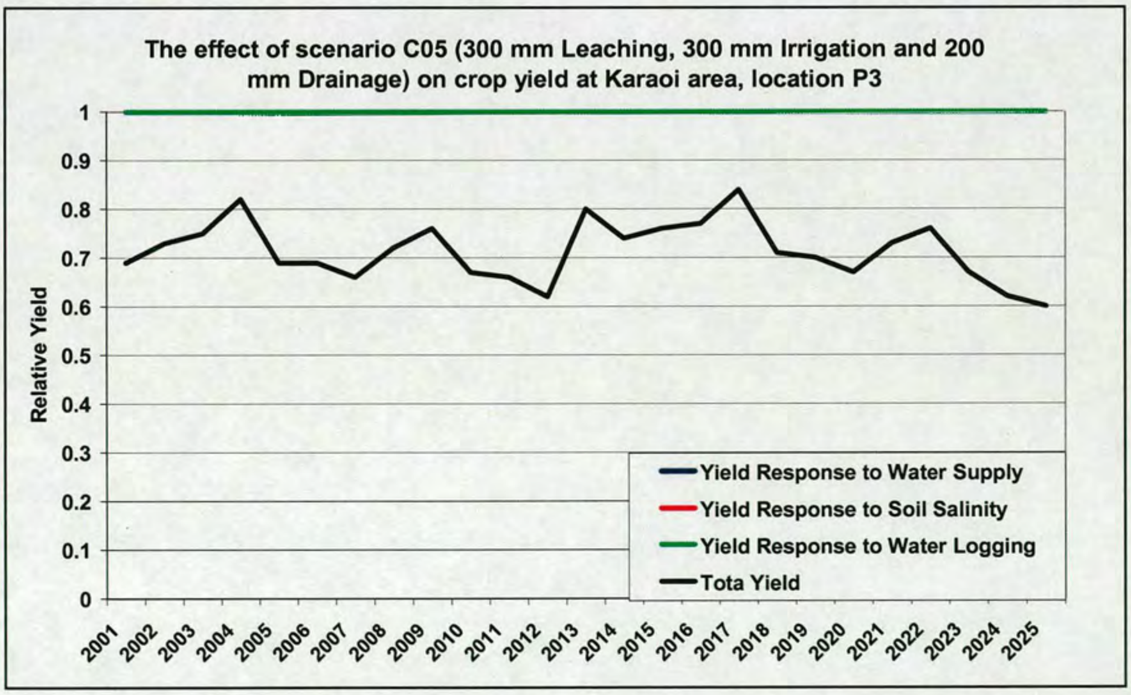
KARAOI AREA, LOCATION P3



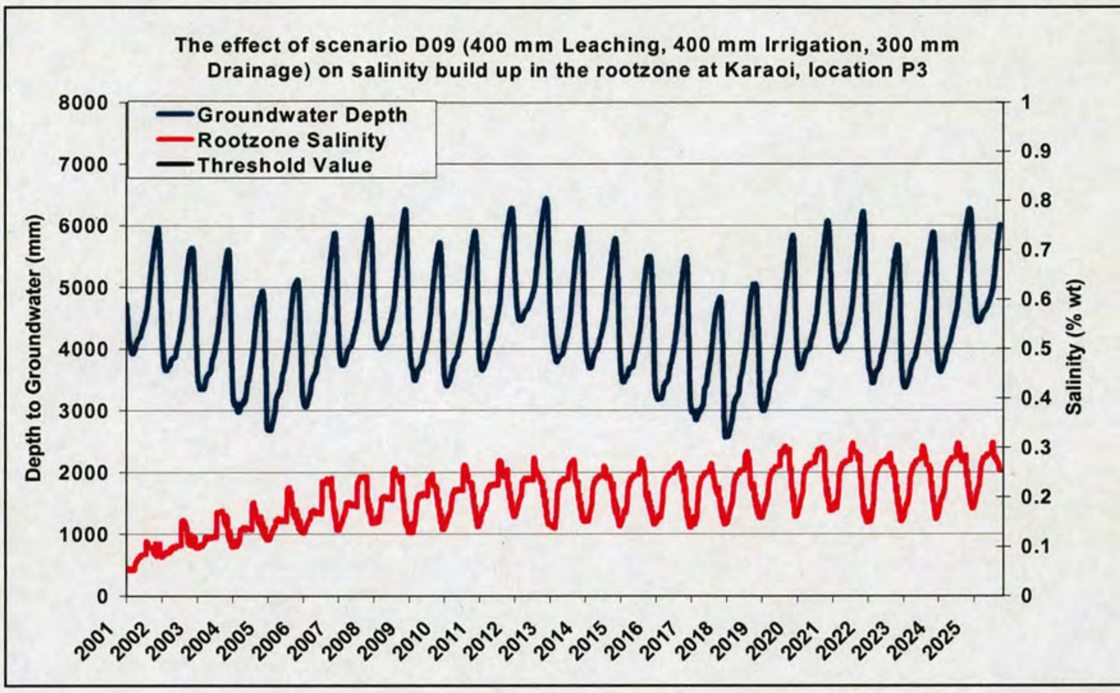


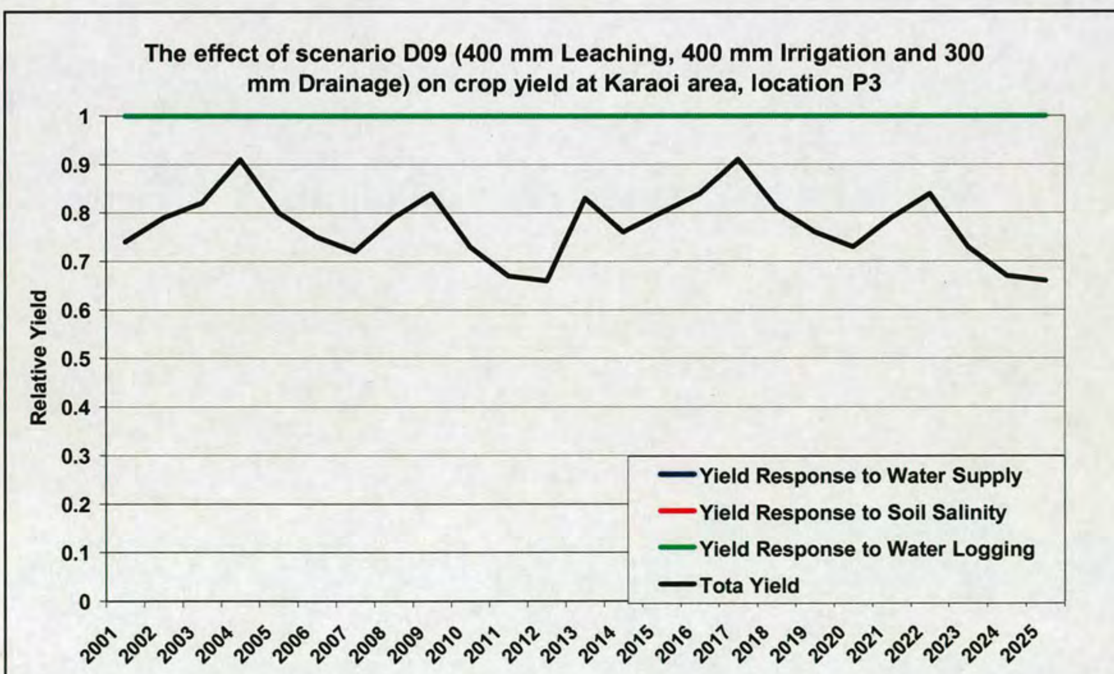
KARAOI AREA, LOCATION P3



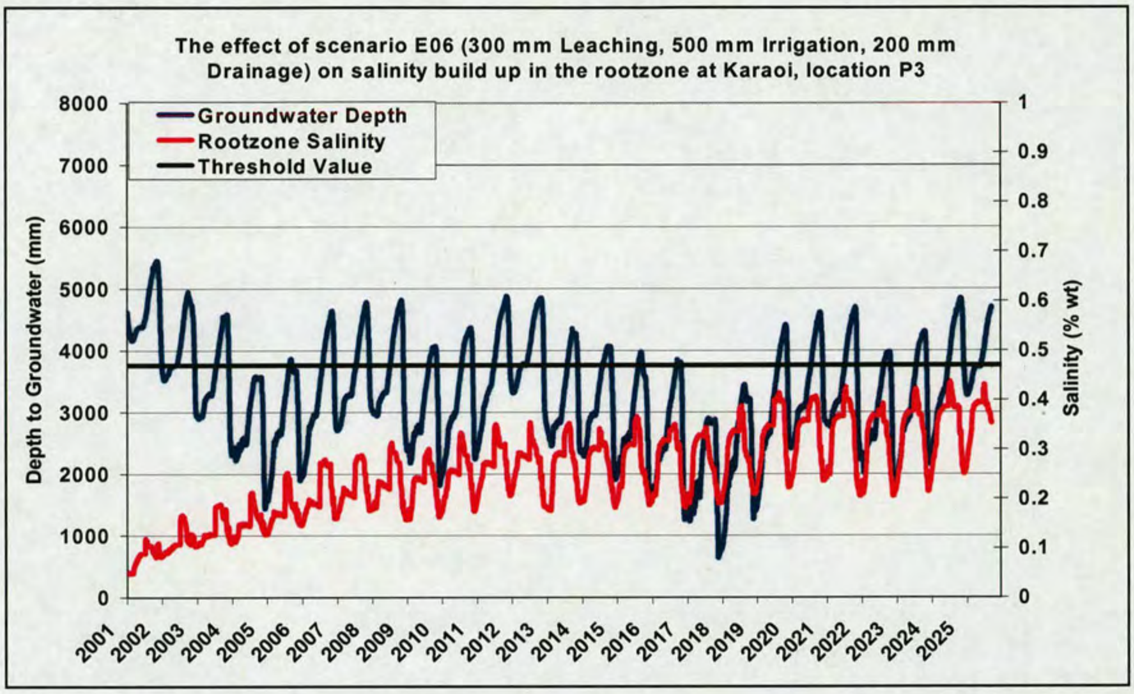


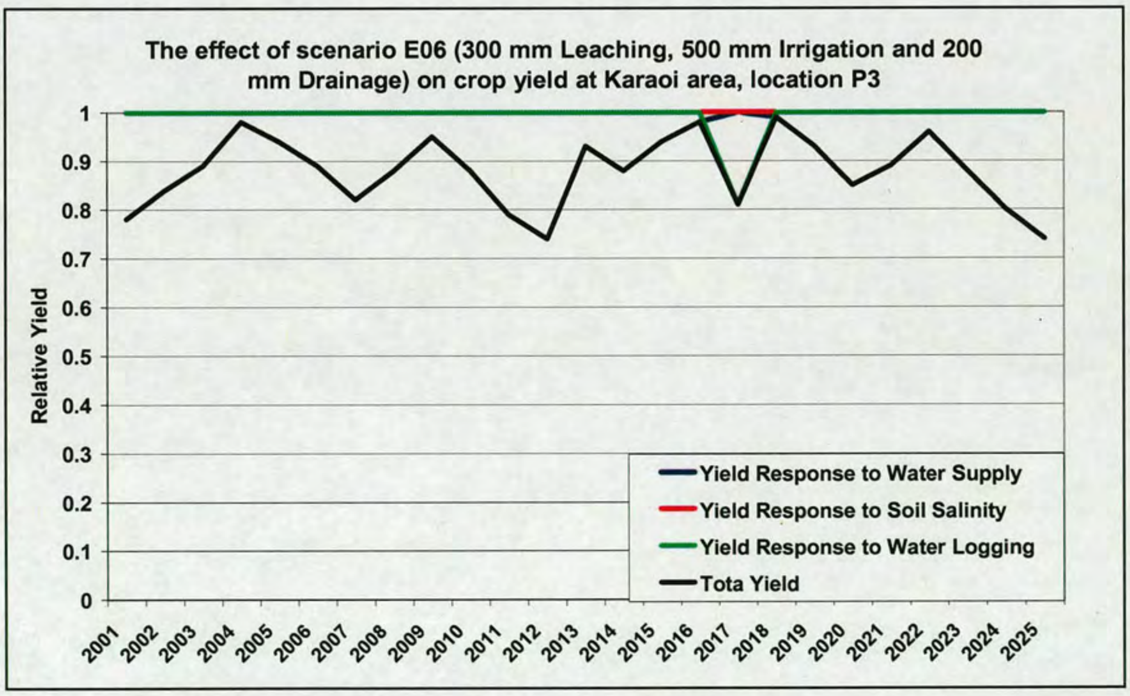
KARAOI AREA, LOCATION P3





KARAOI AREA, LOCATION P3





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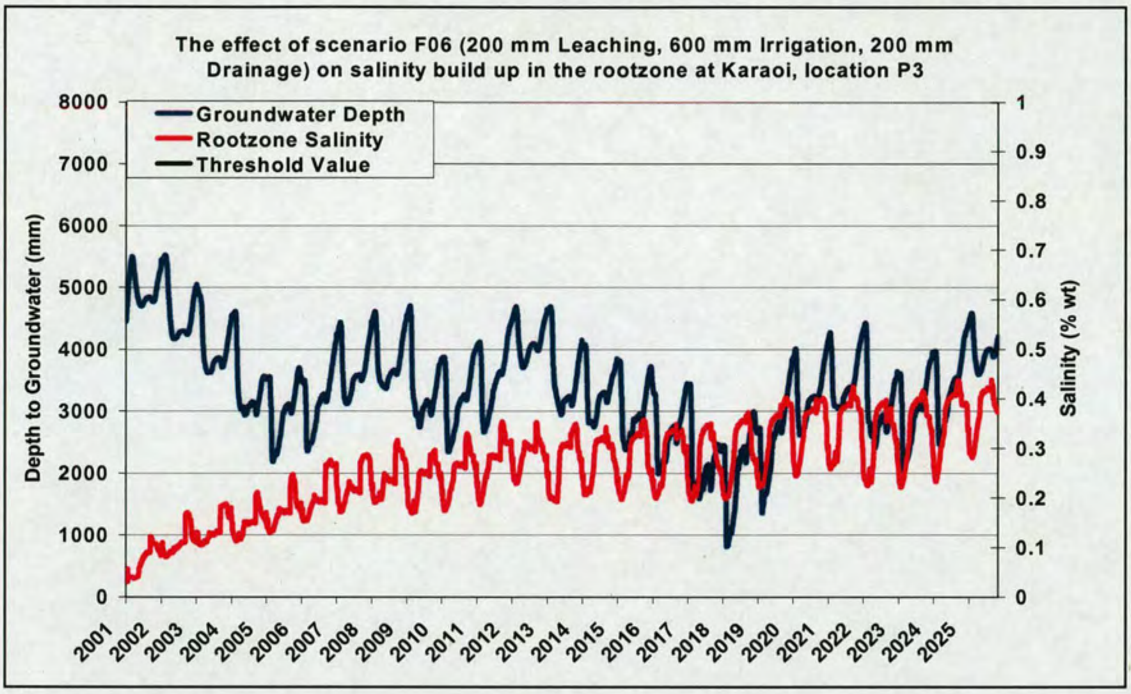

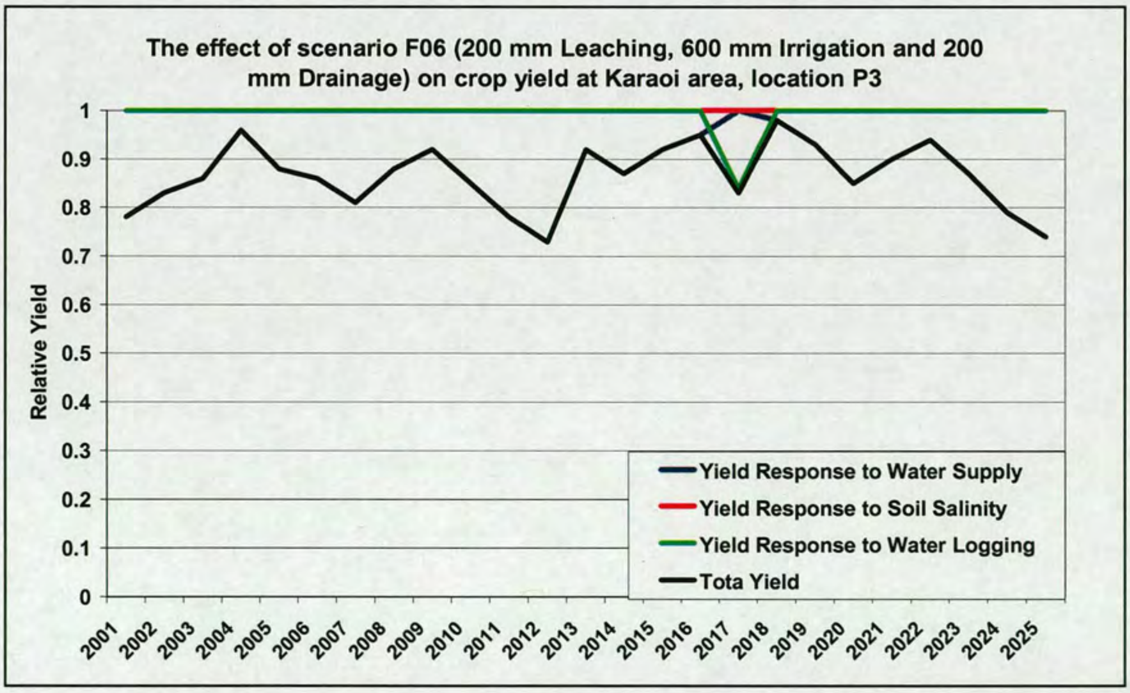

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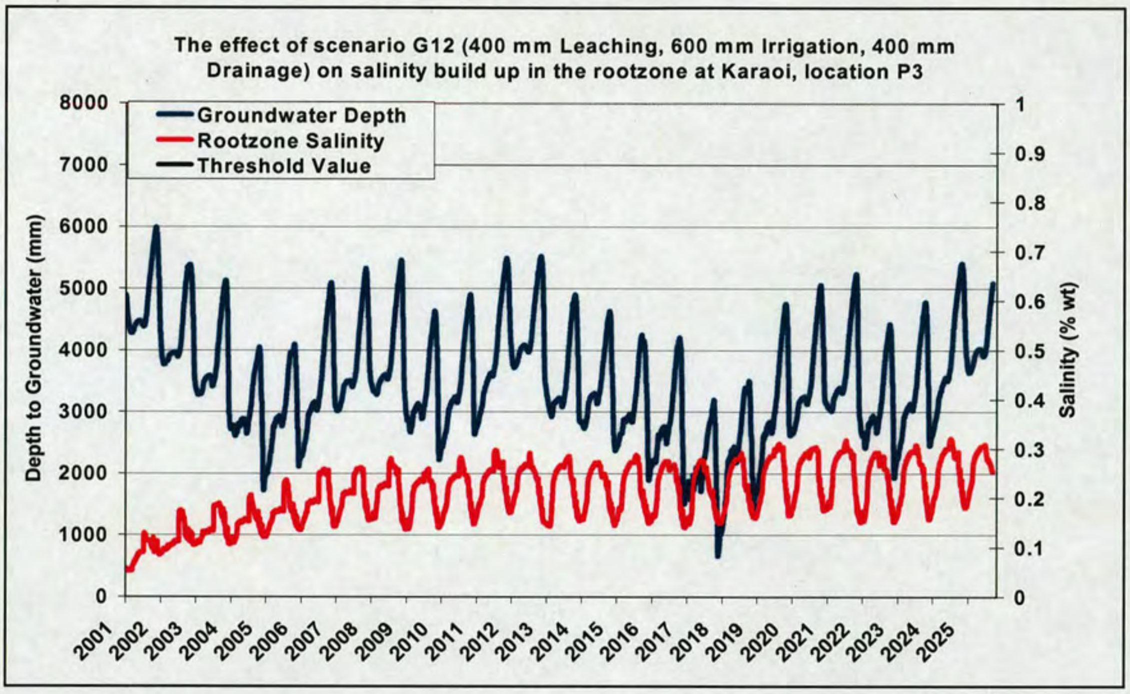
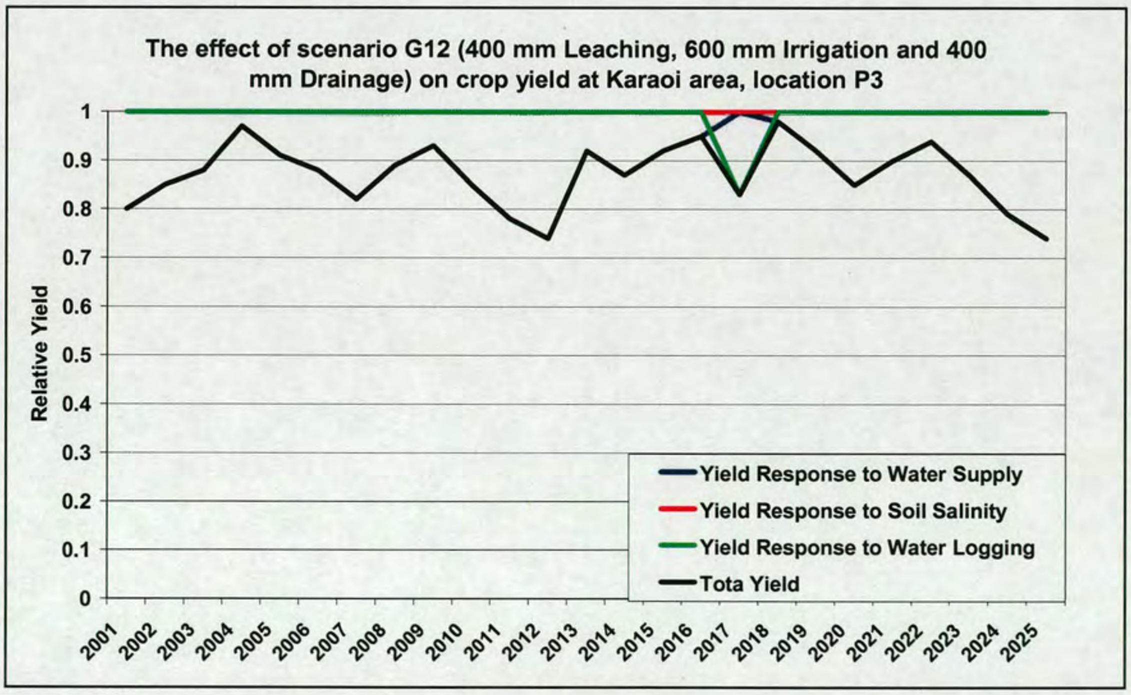
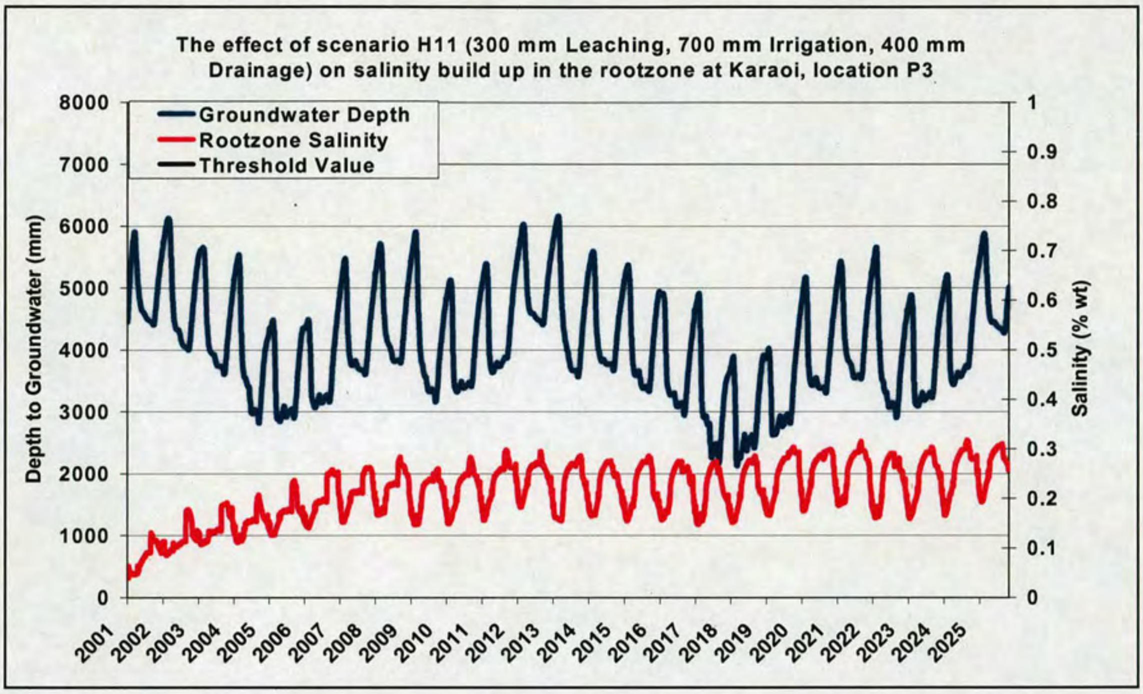
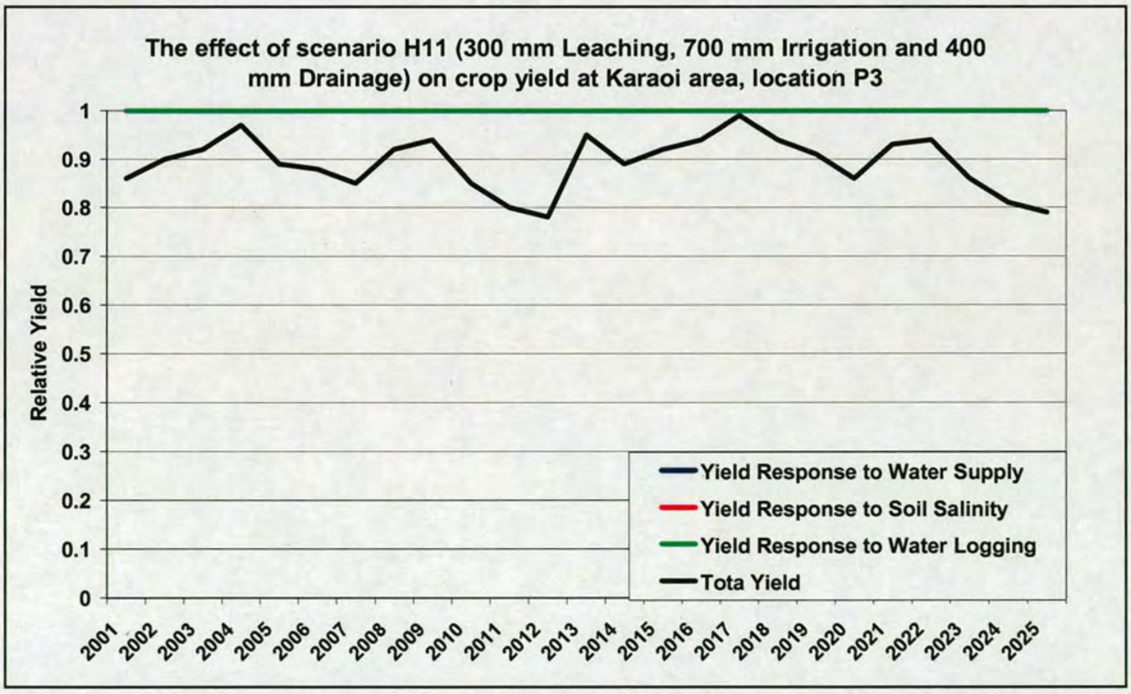




KARAOI AREA, LOCATION P3





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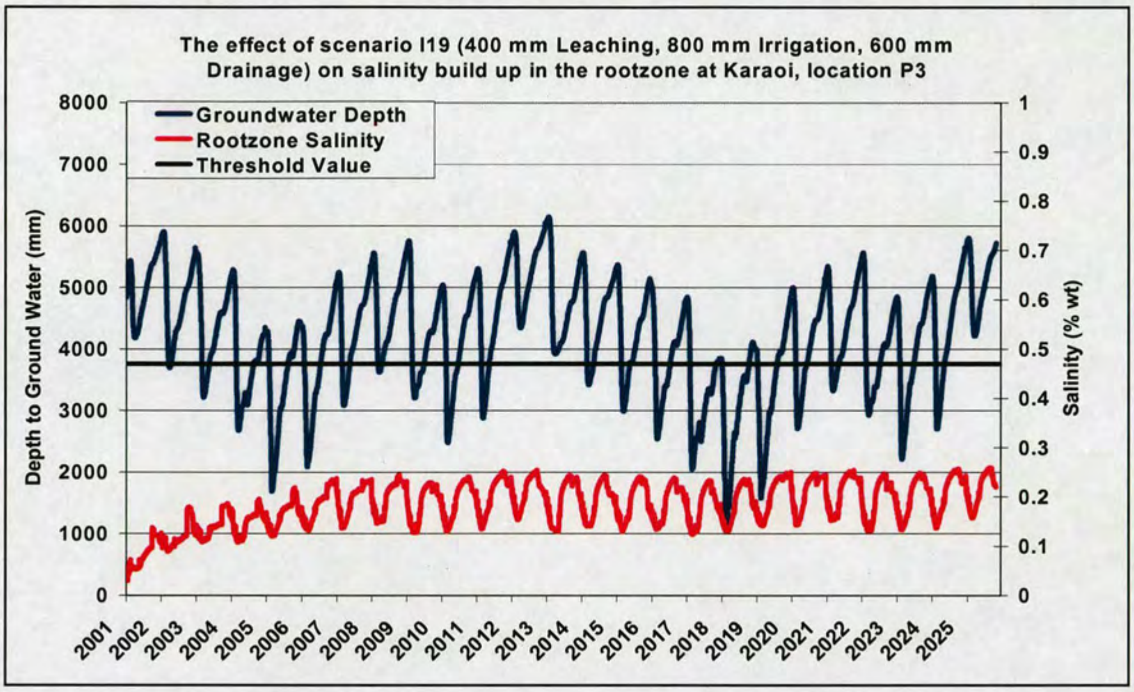

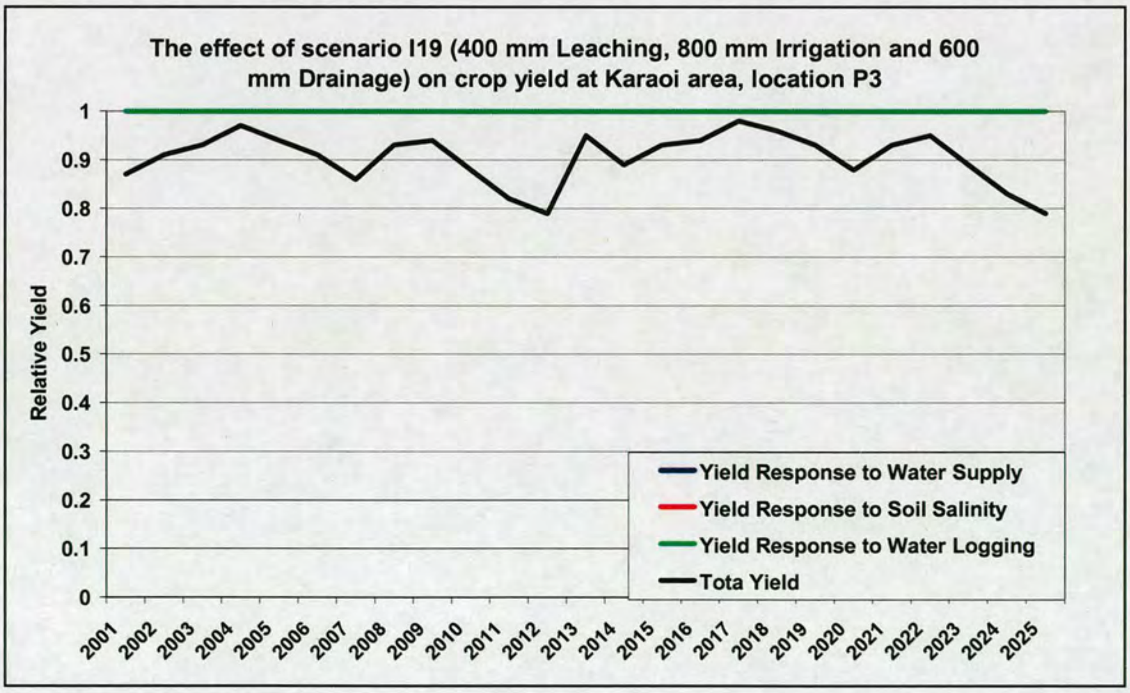

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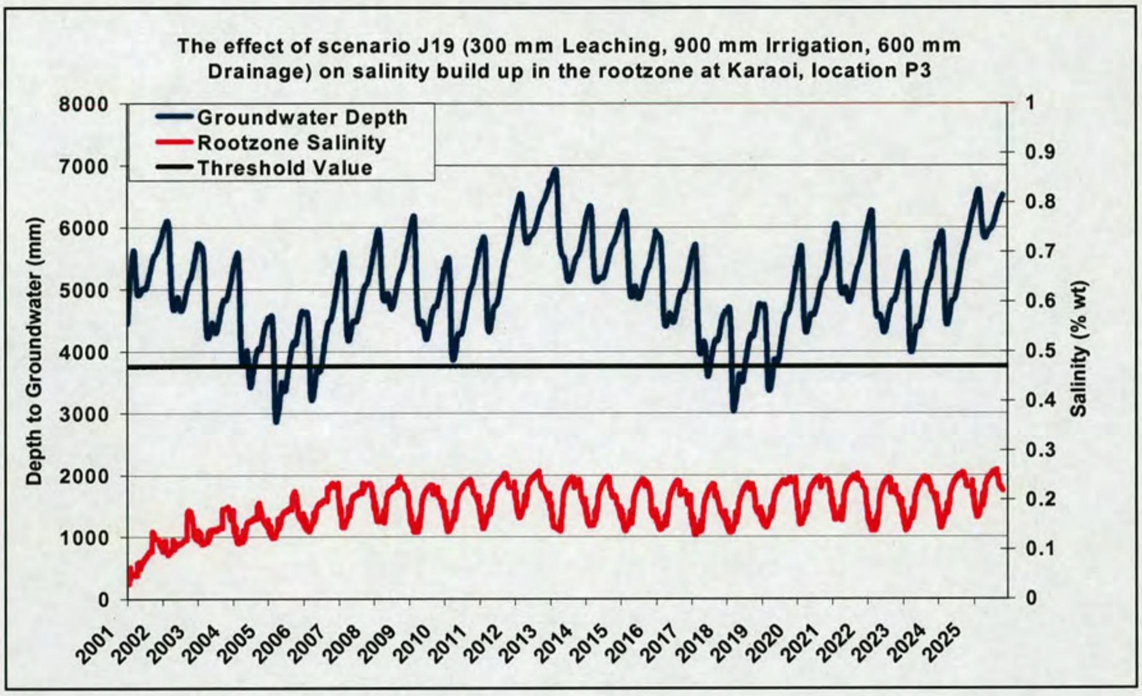
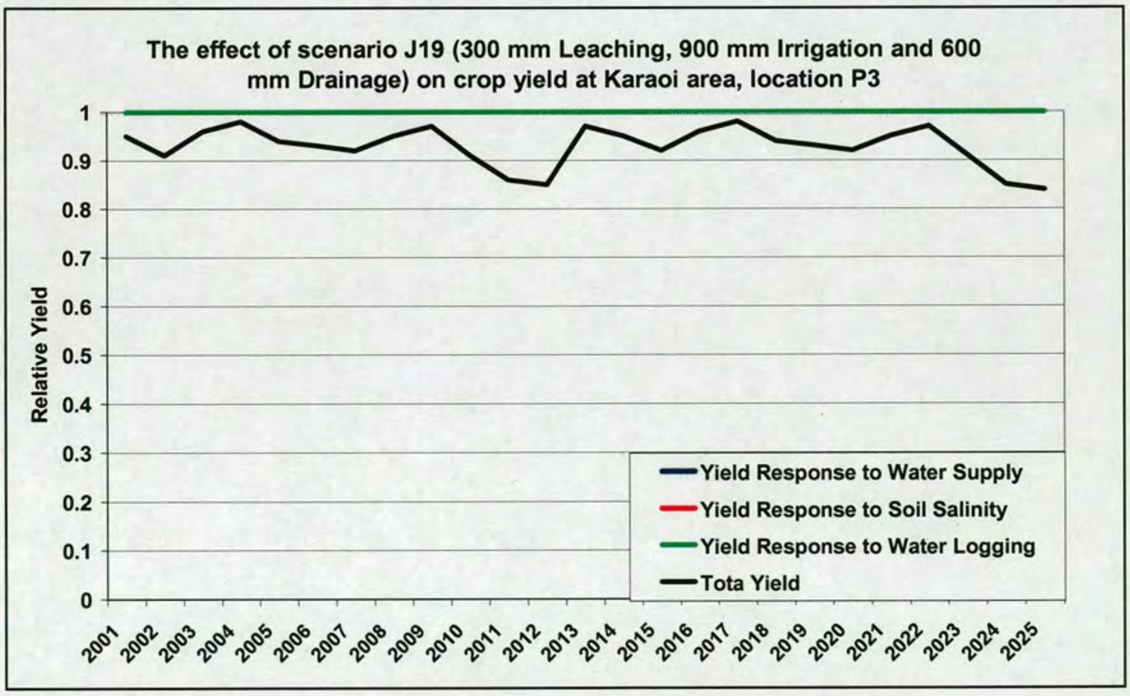
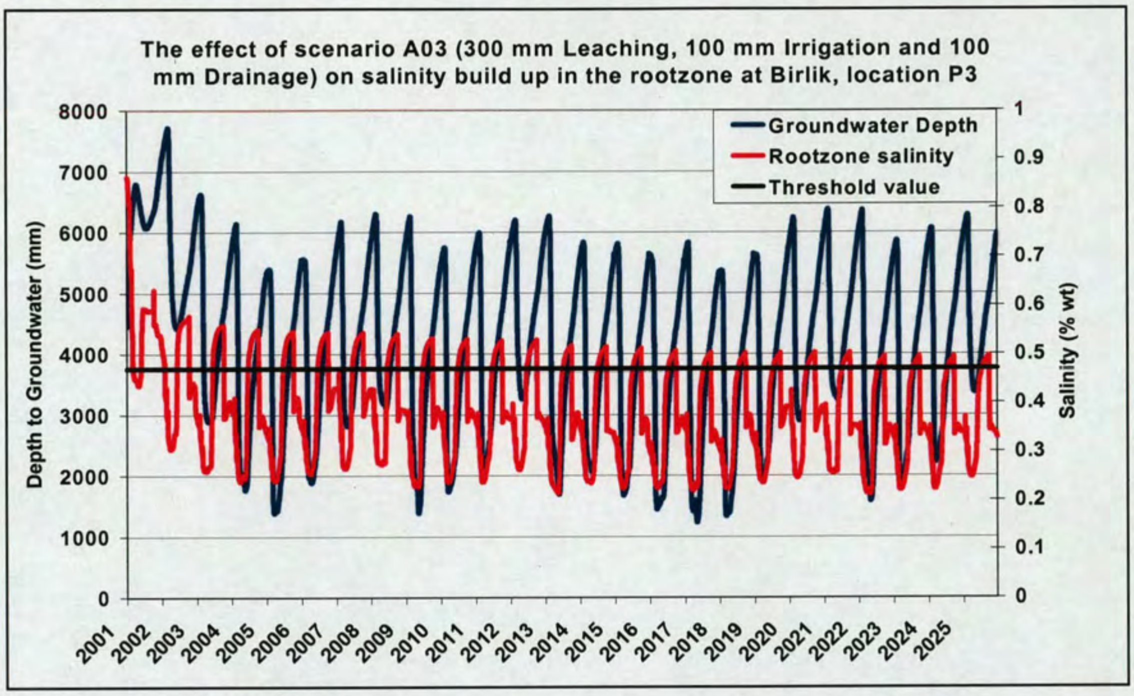
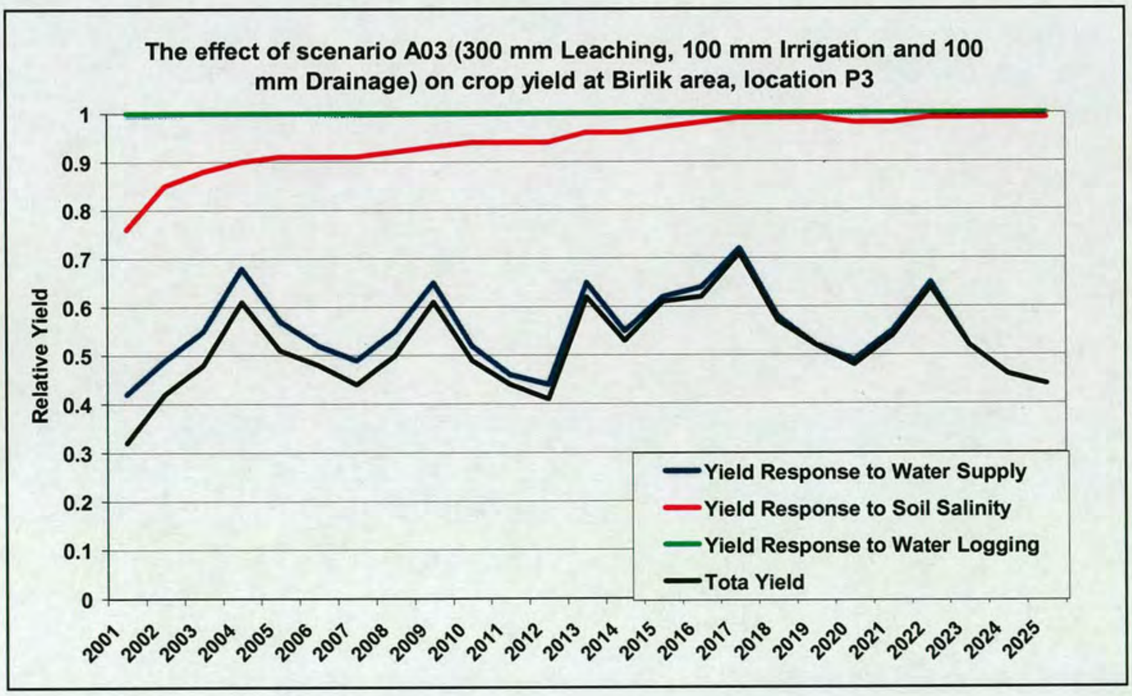


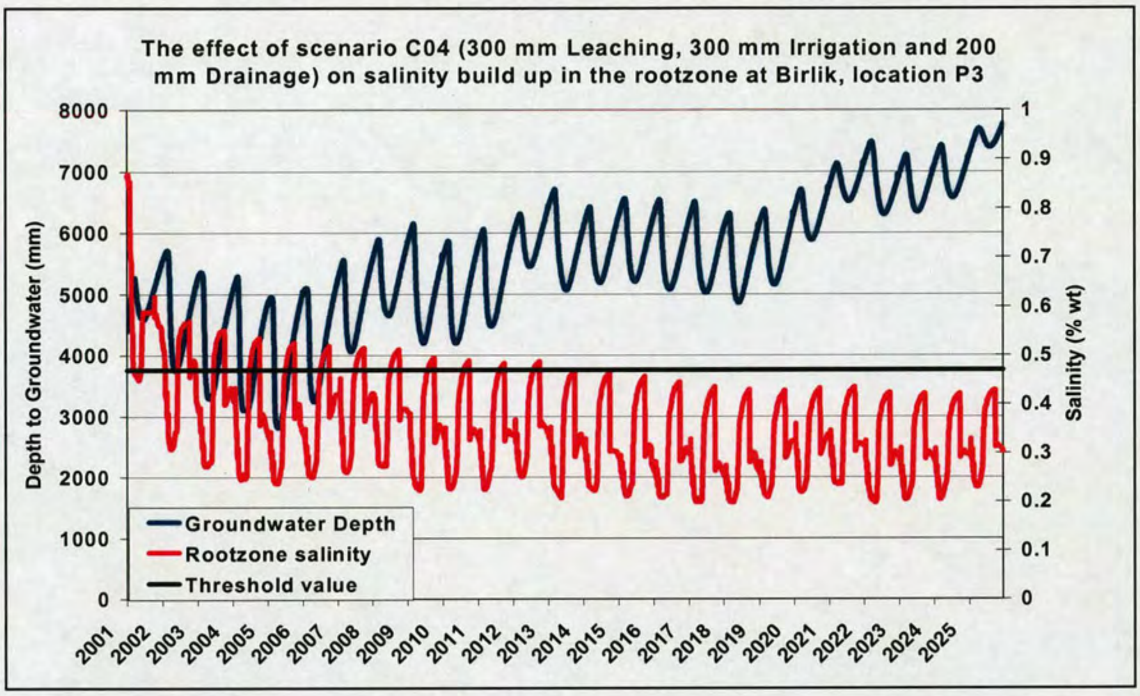


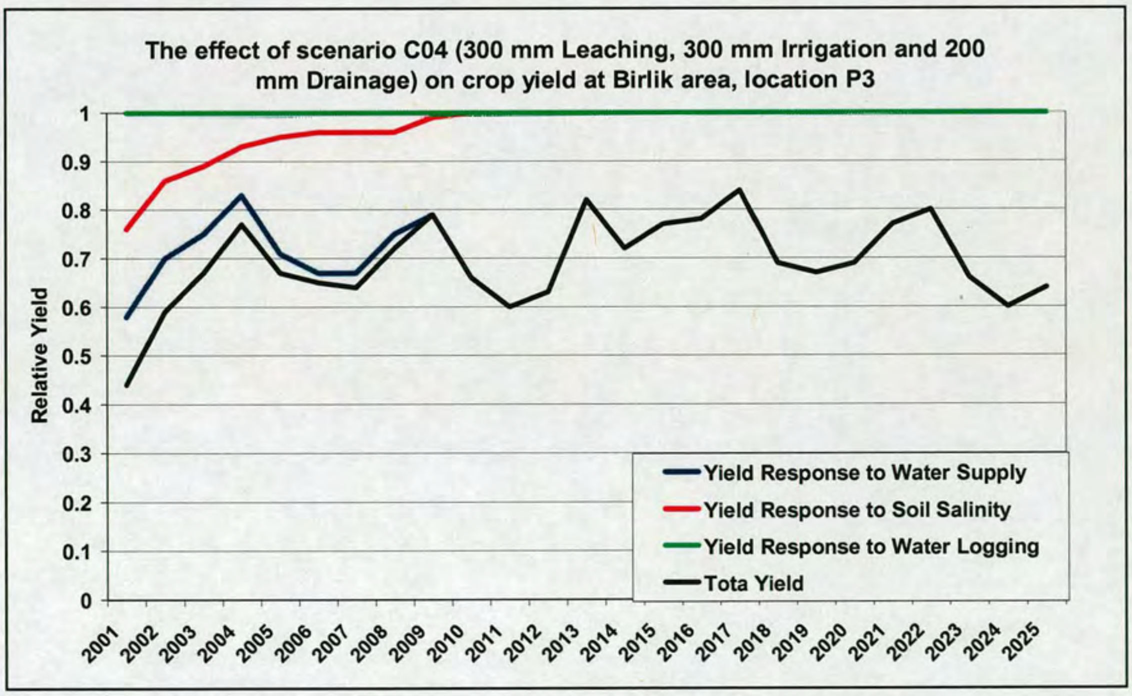
BIRLIK AREA, LOCATION P3





BIRLIK AREA, LOCATION P3





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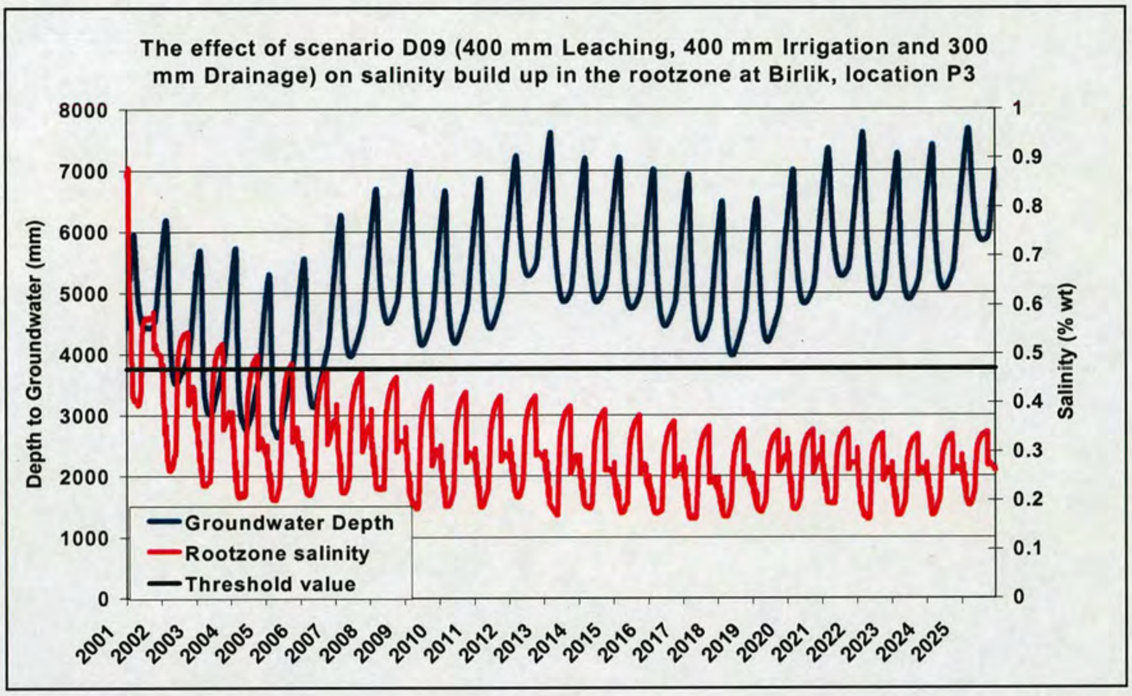

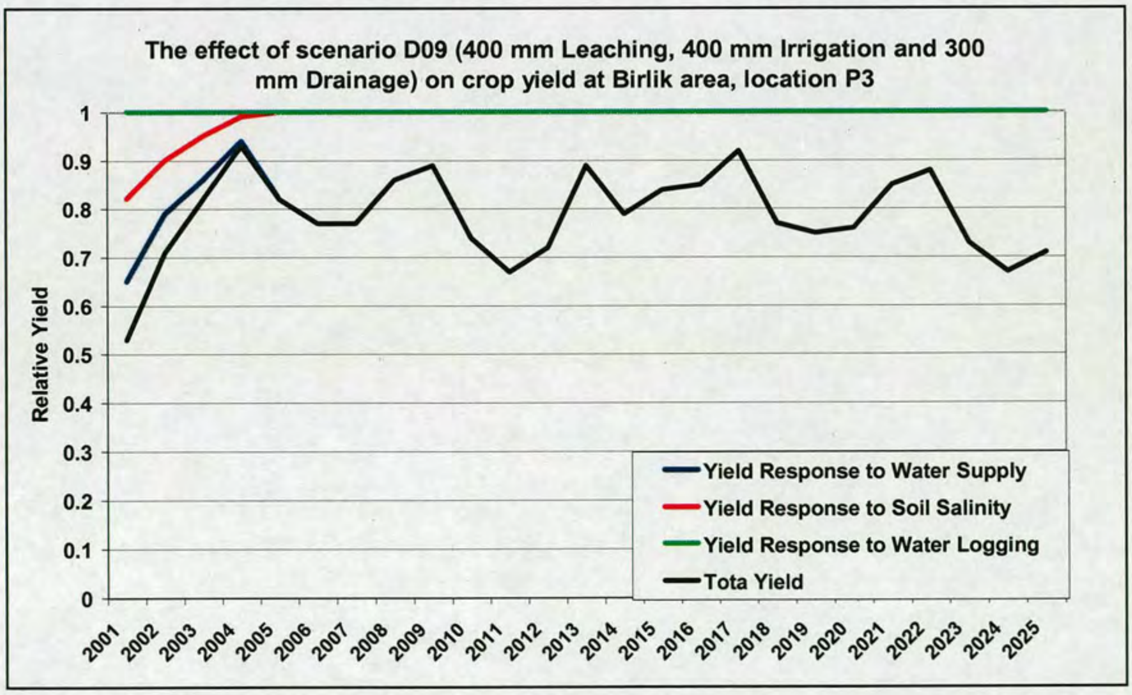

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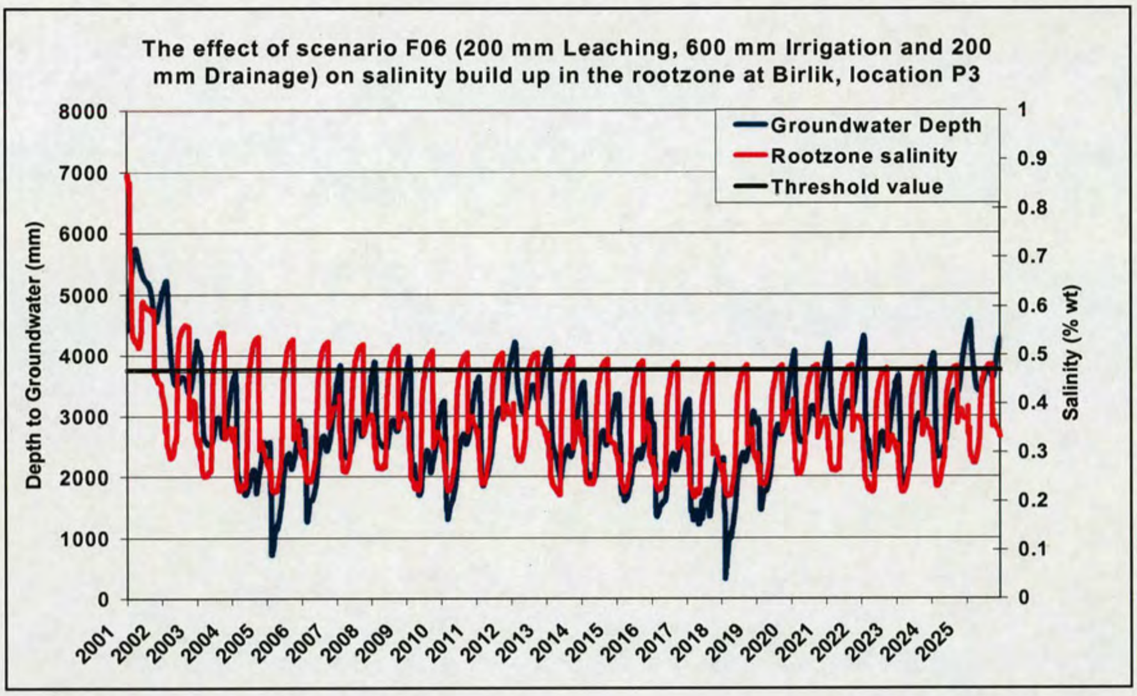

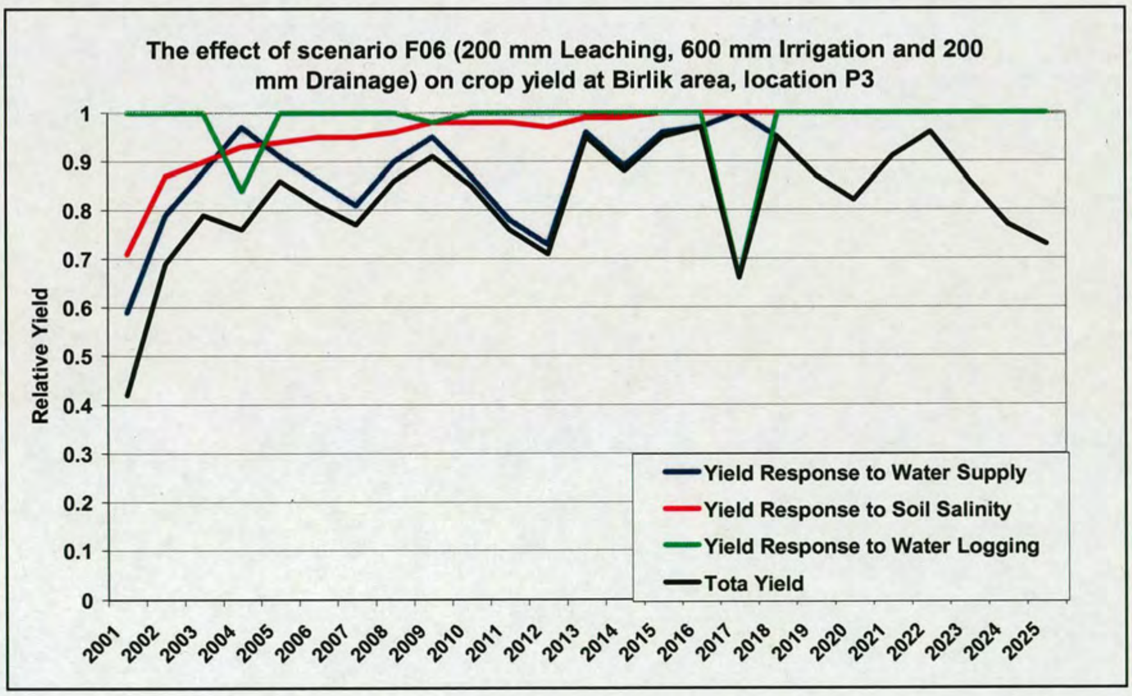

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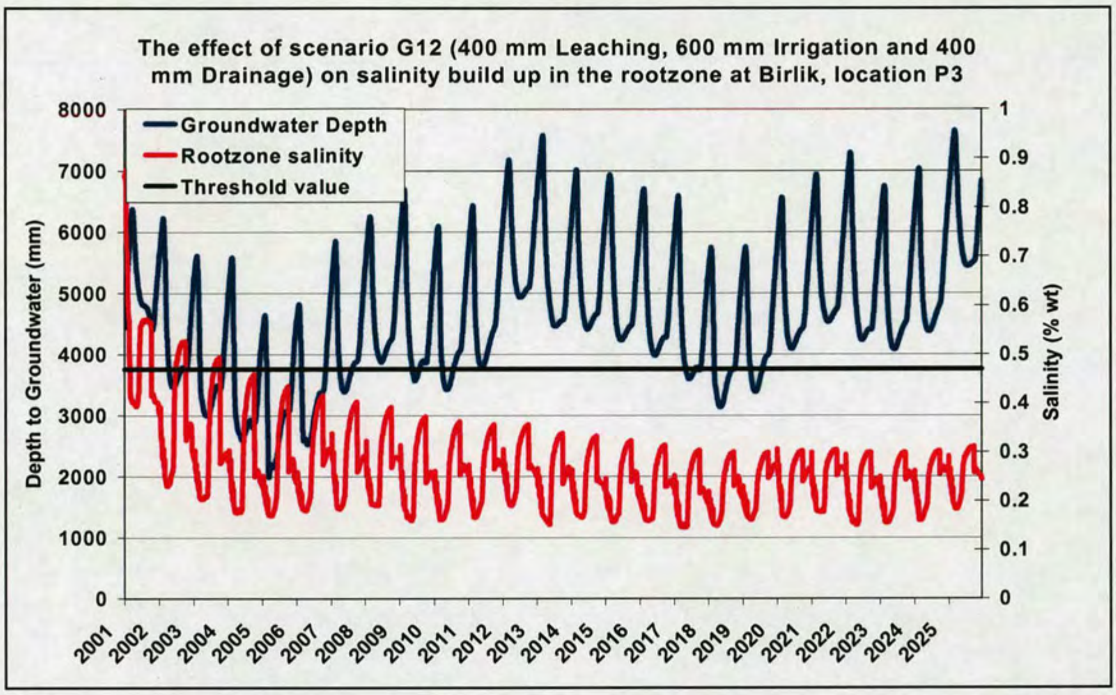

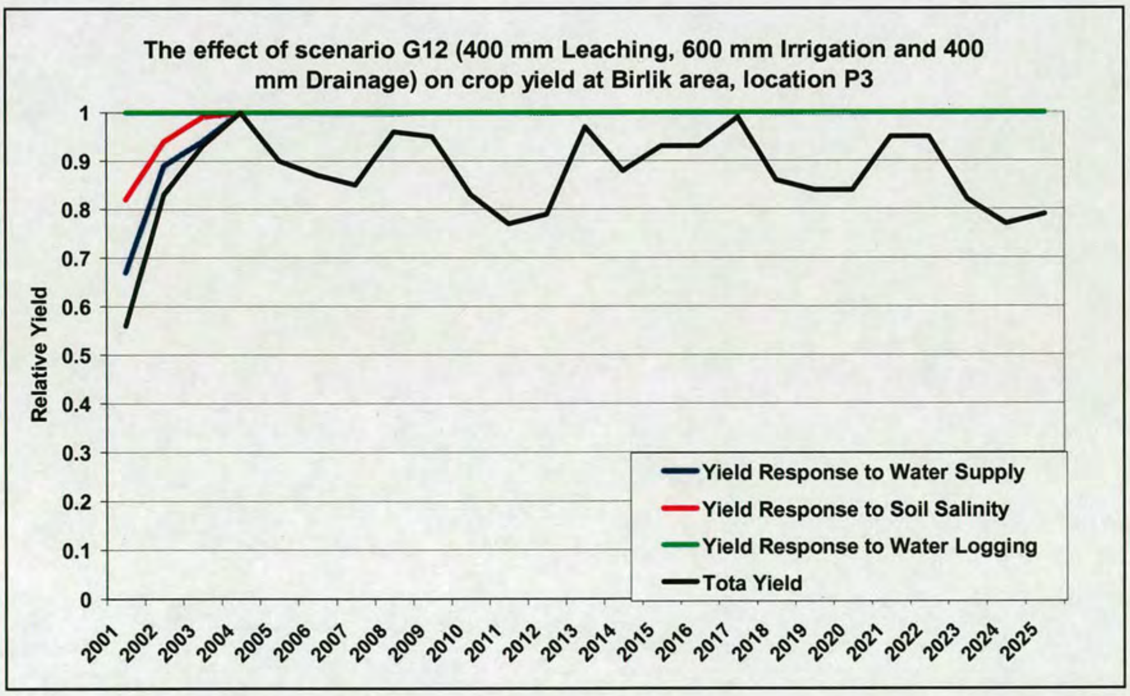

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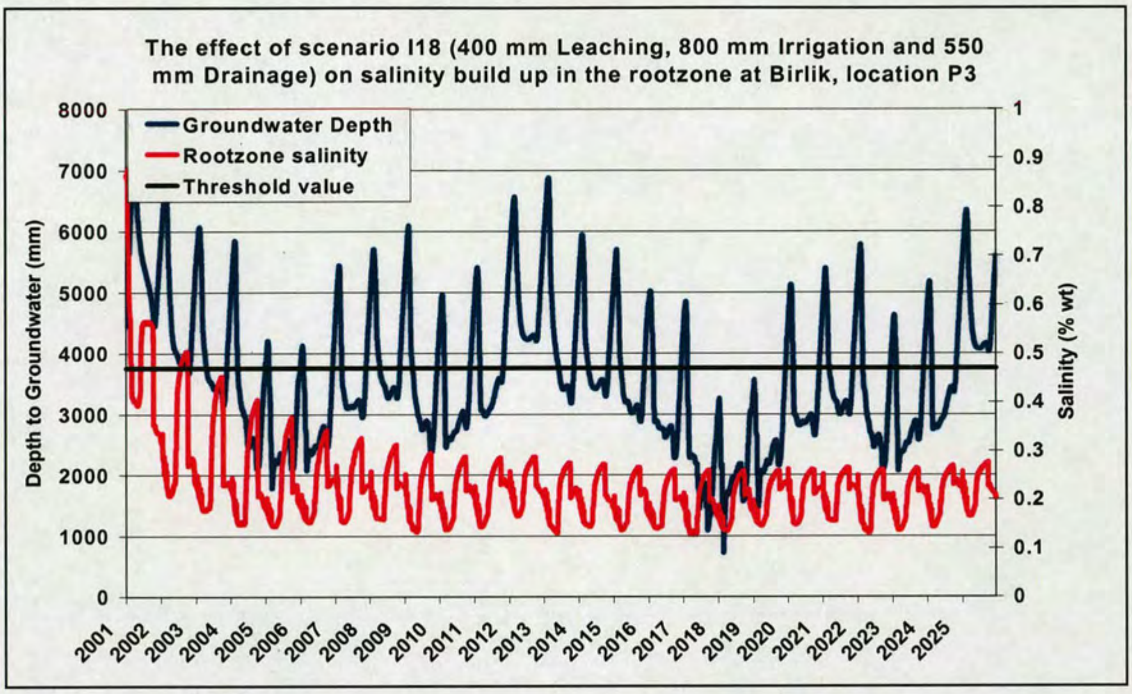
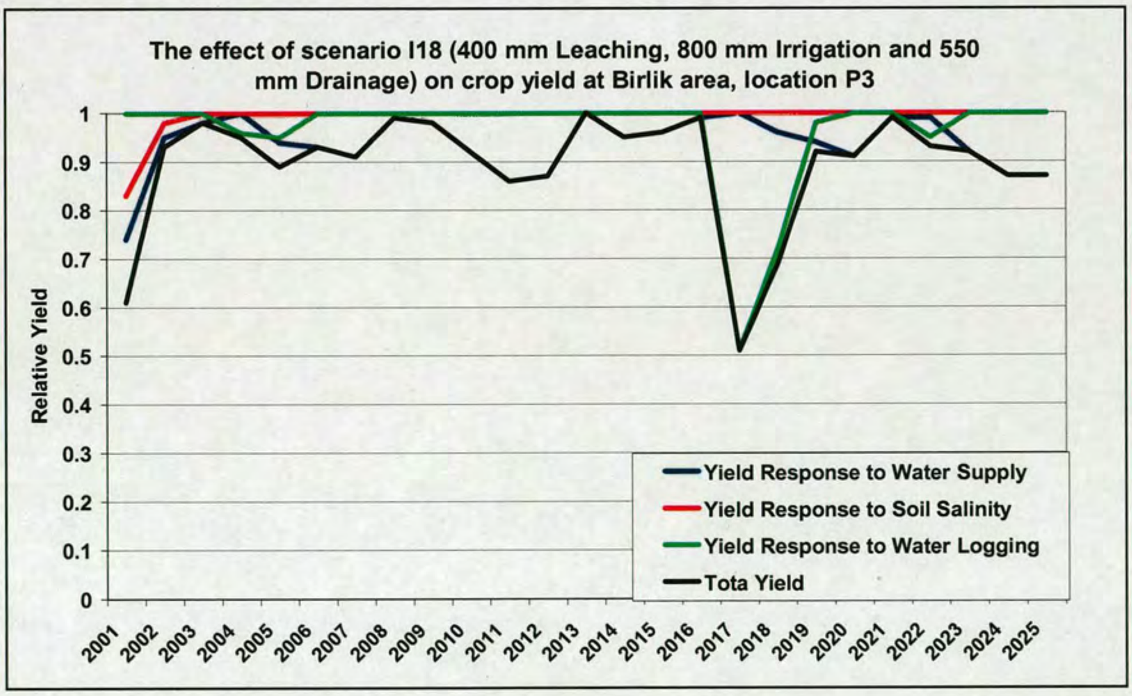
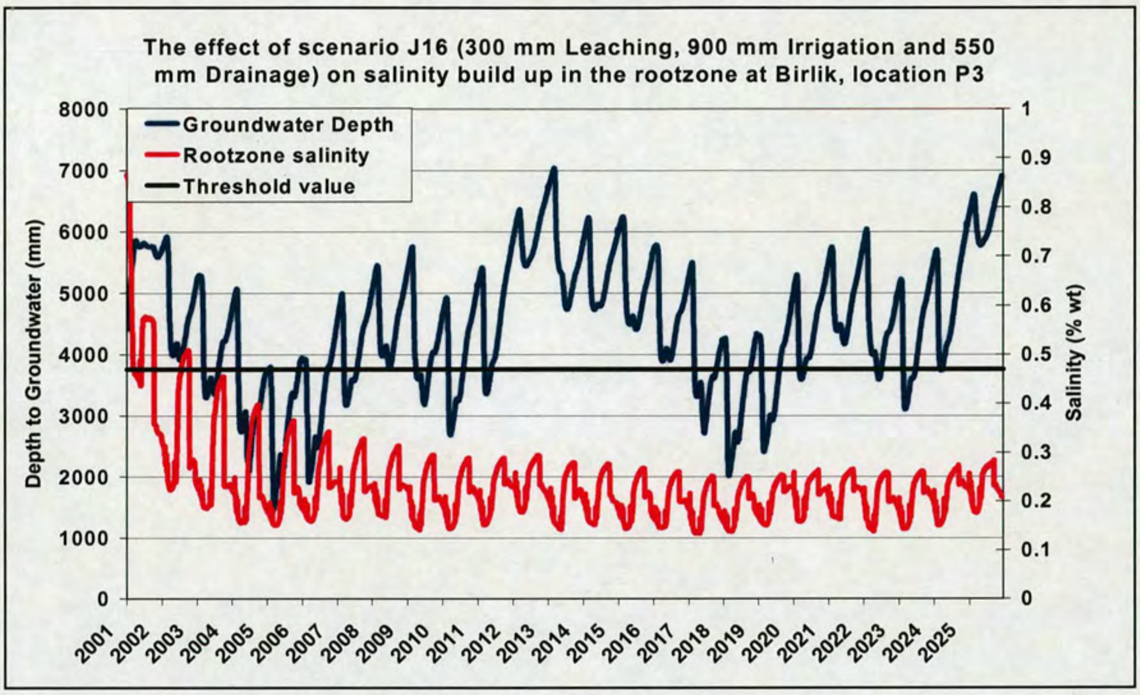
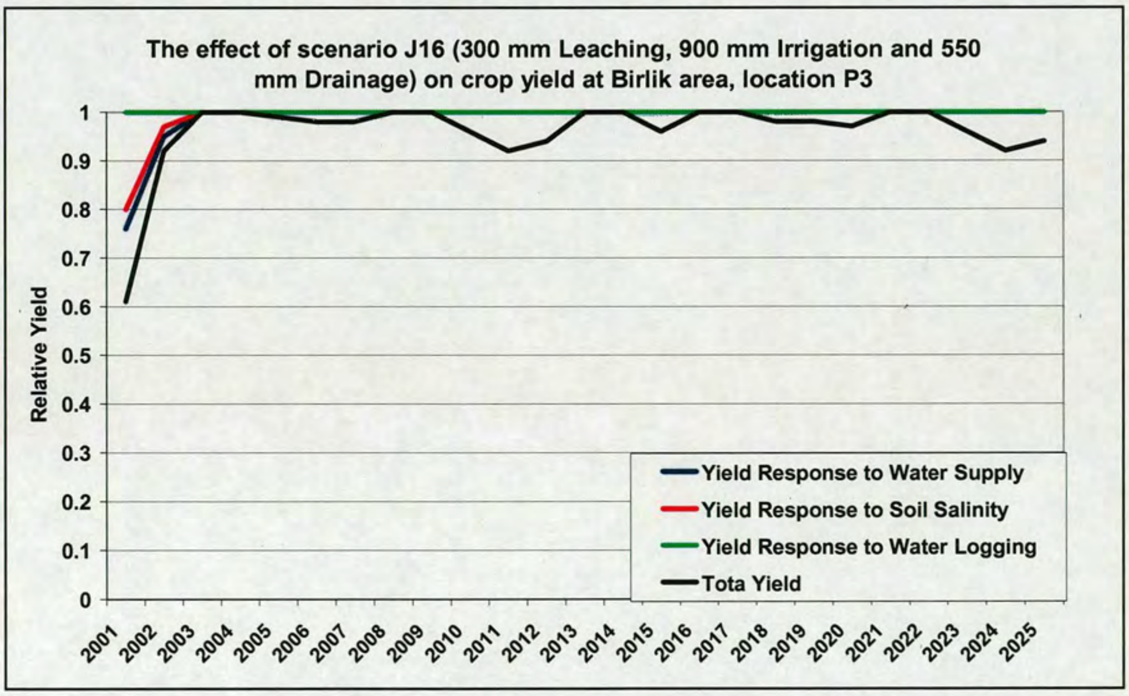


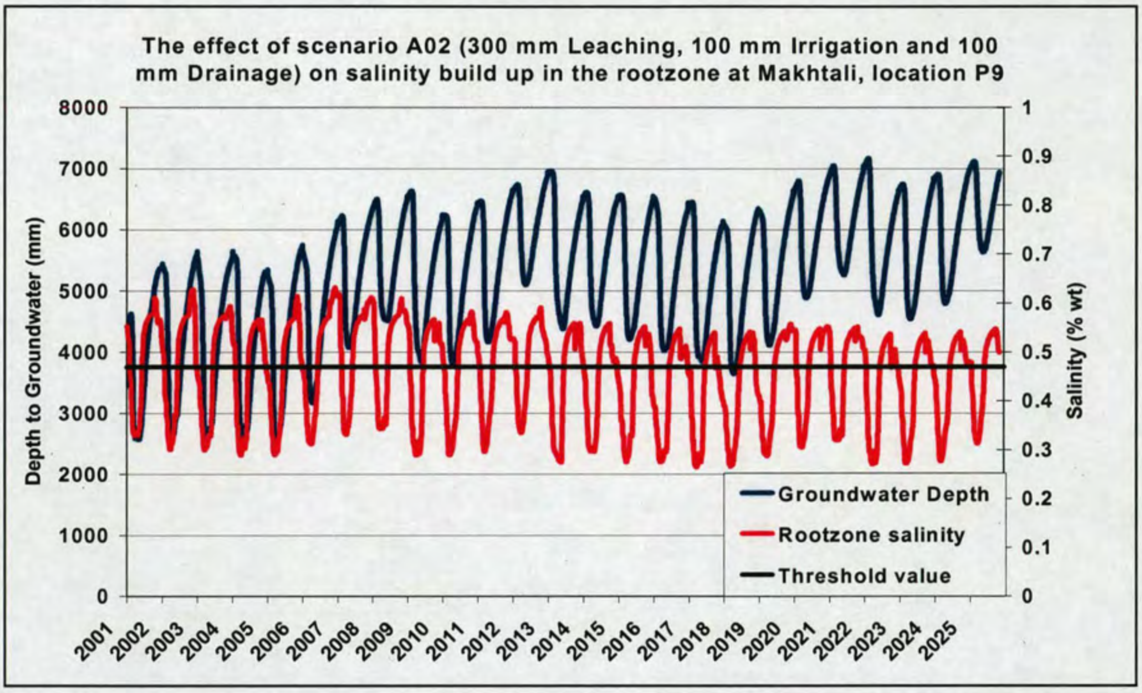


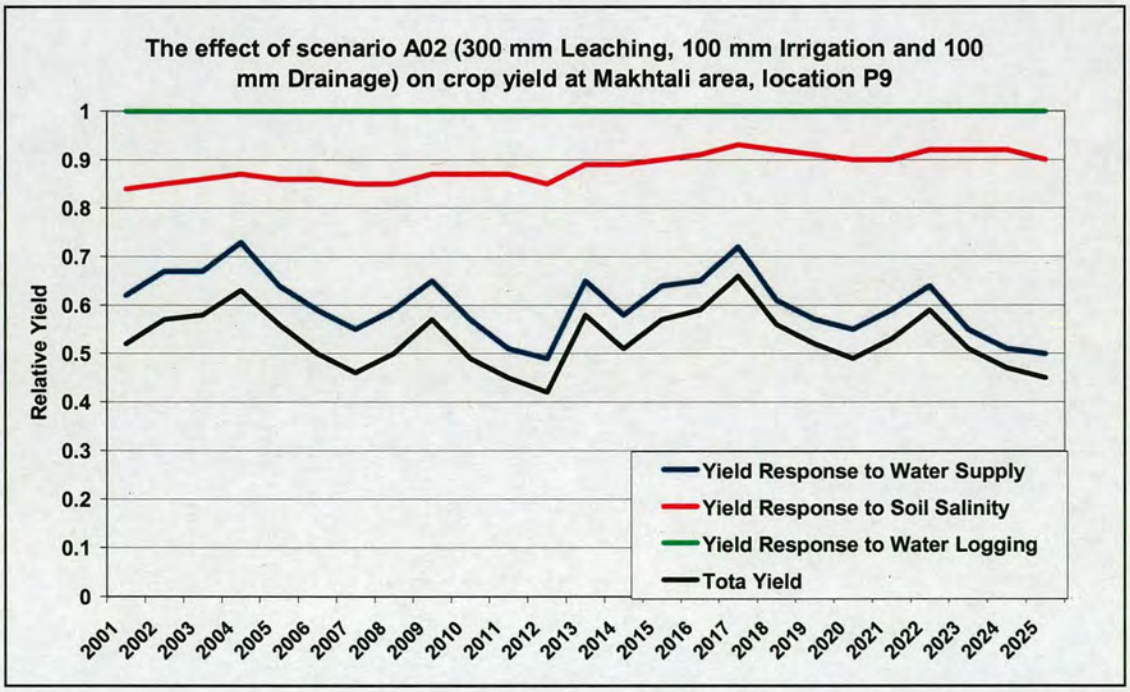
BIRLIK AREA, LOCATION P3



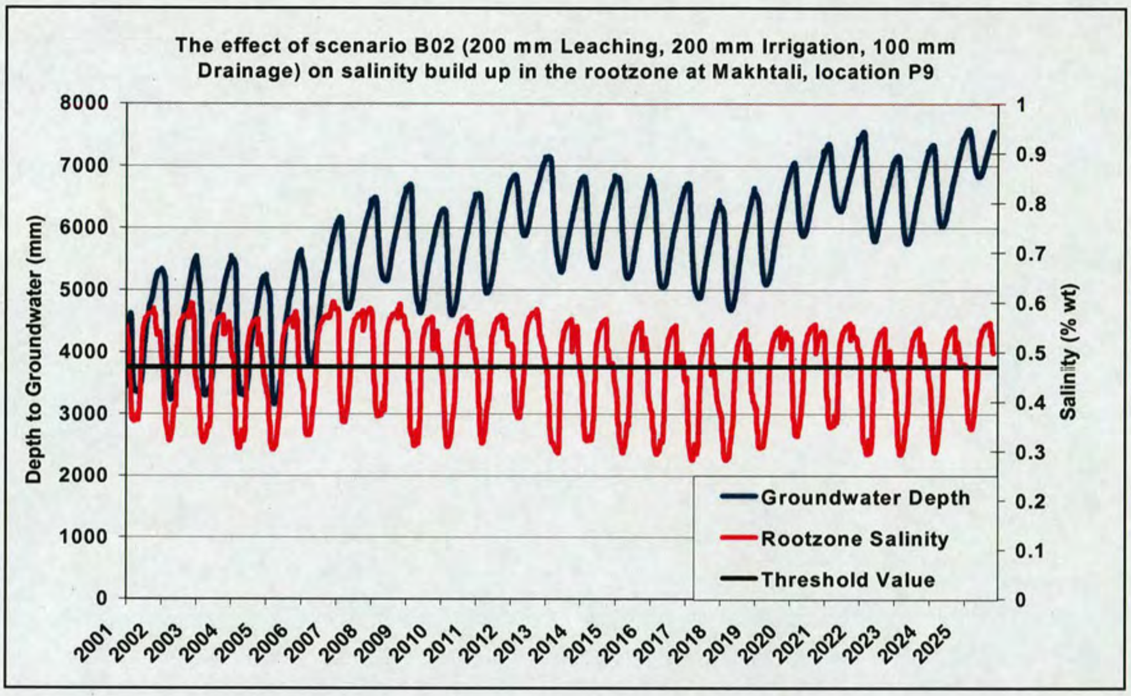


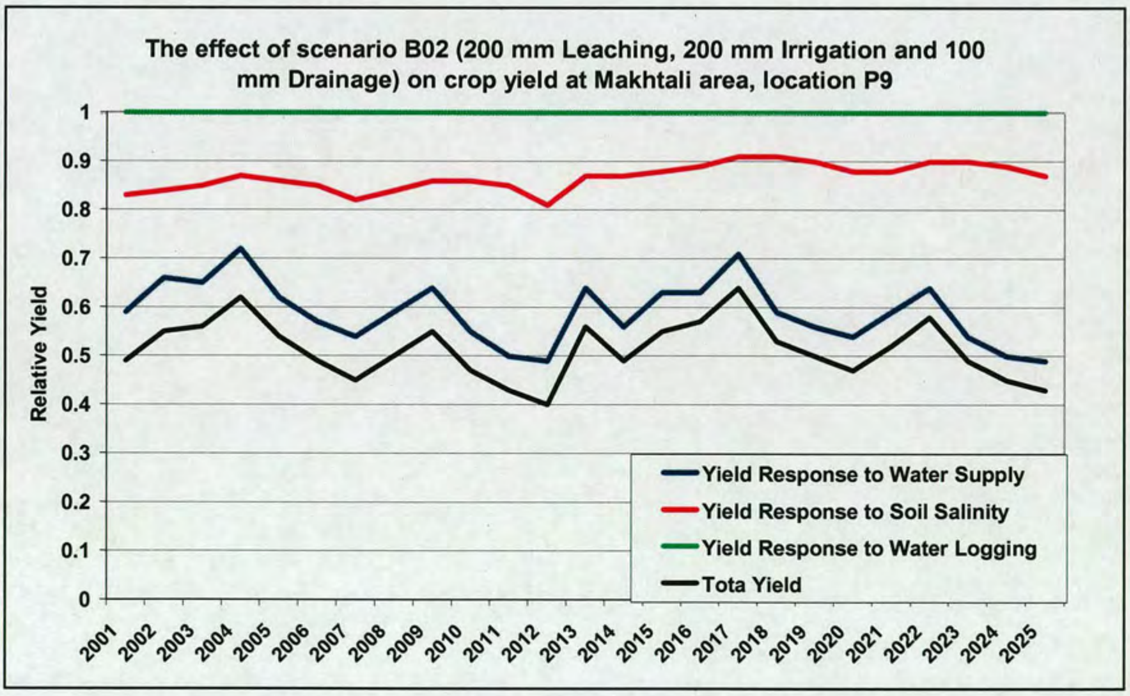
MAKHTALI AREA, LOCATION P9



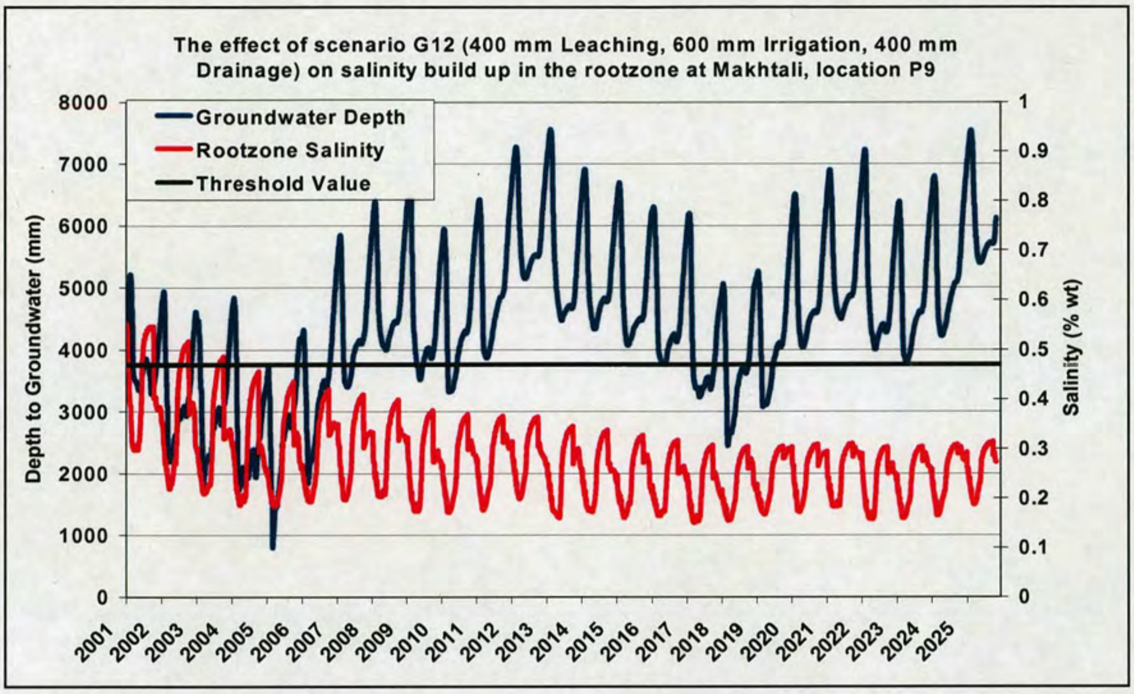


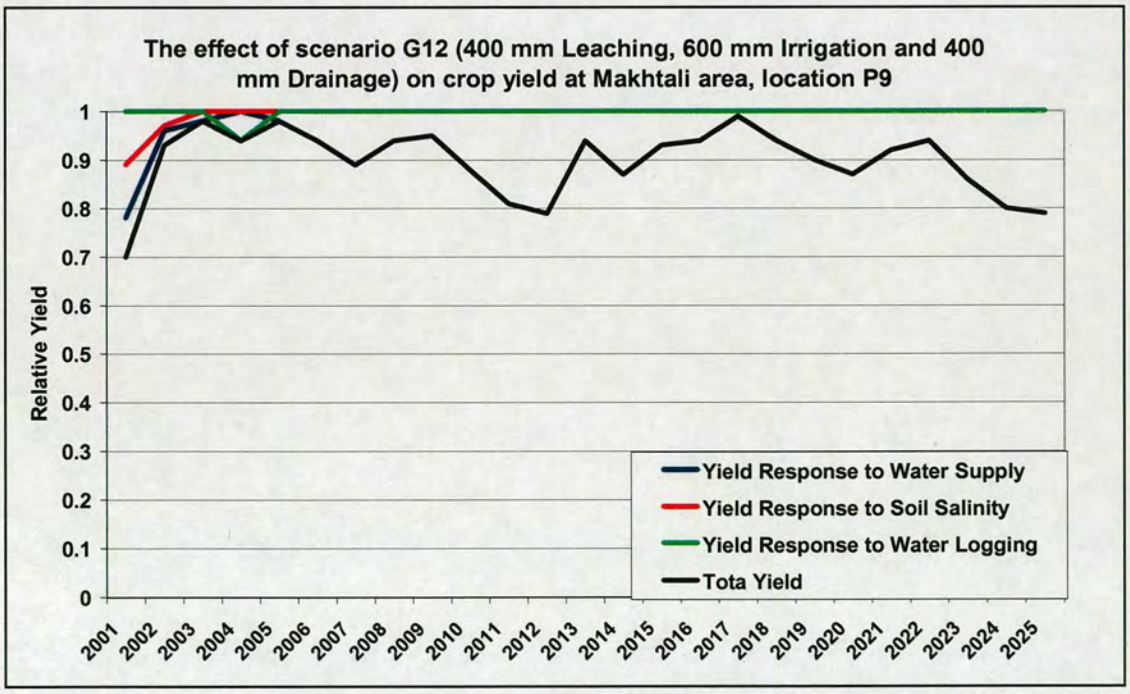
MAKHTALI AREA, LOCATION P9





MAKHTALI AREA, LOCATION P9





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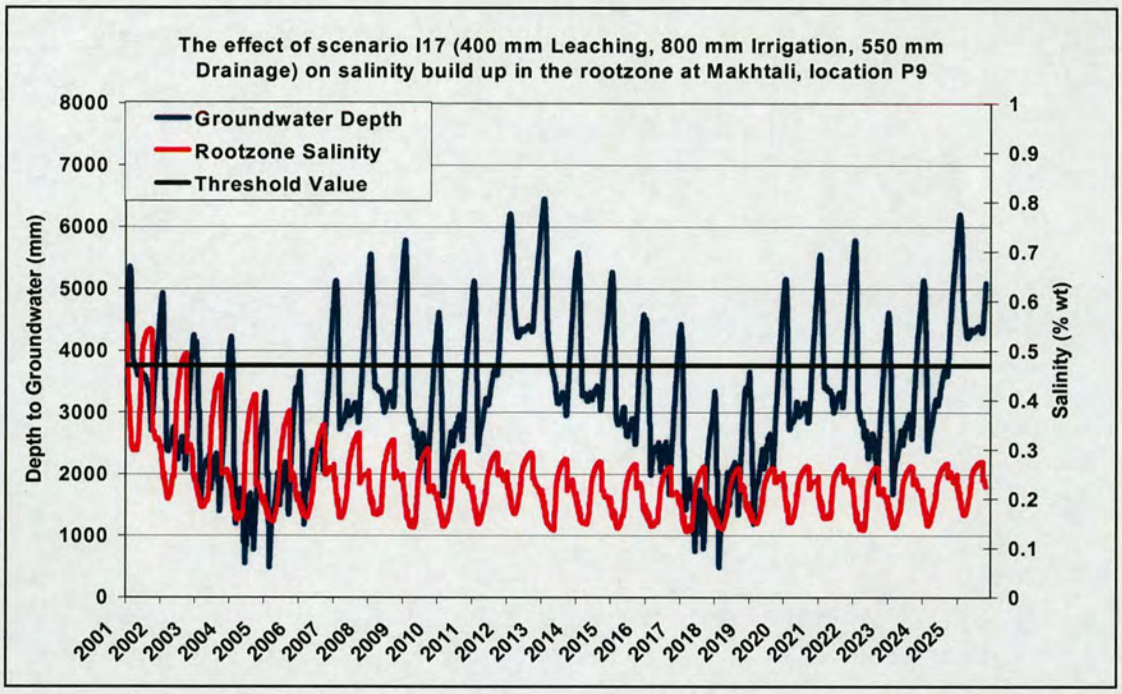

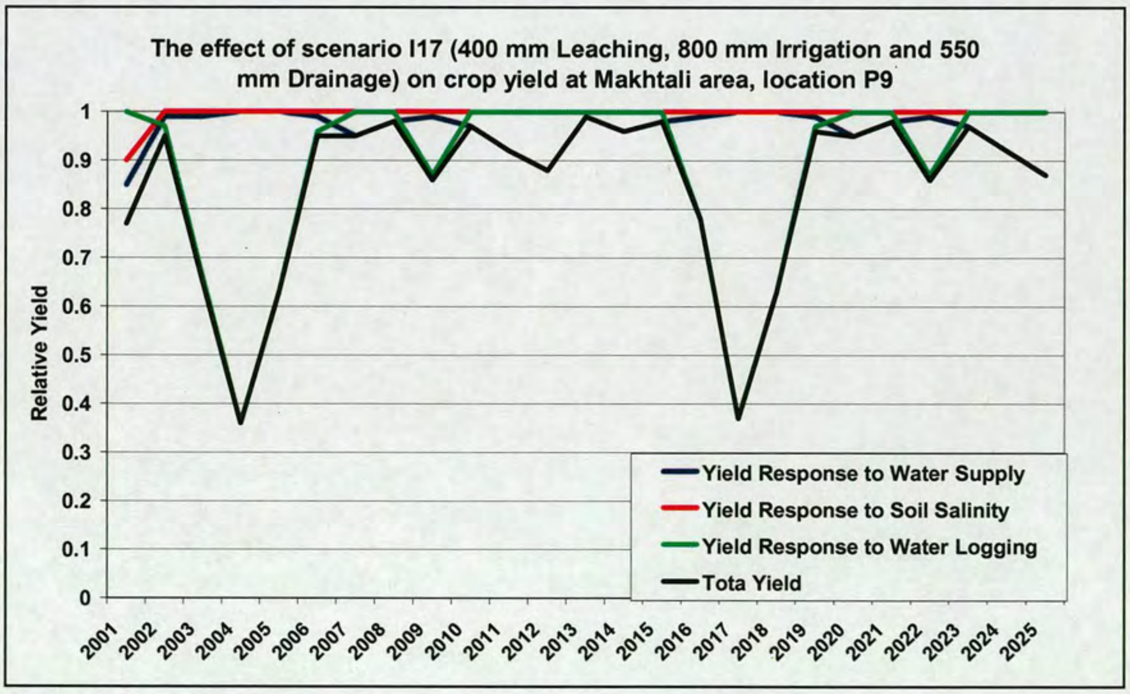

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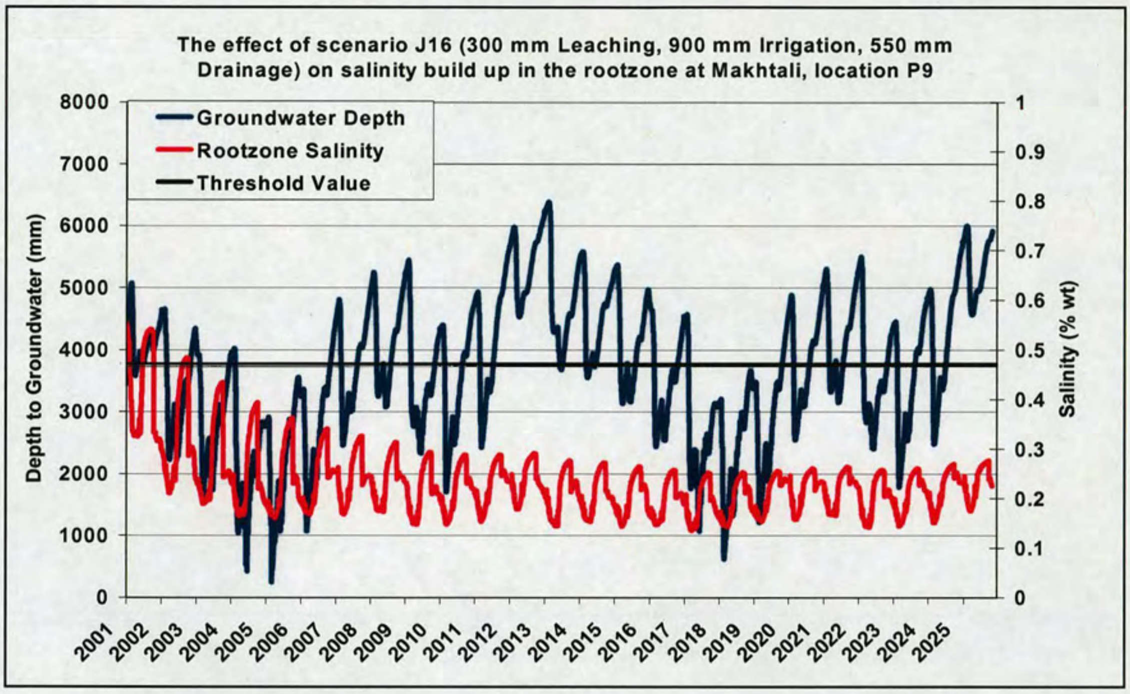
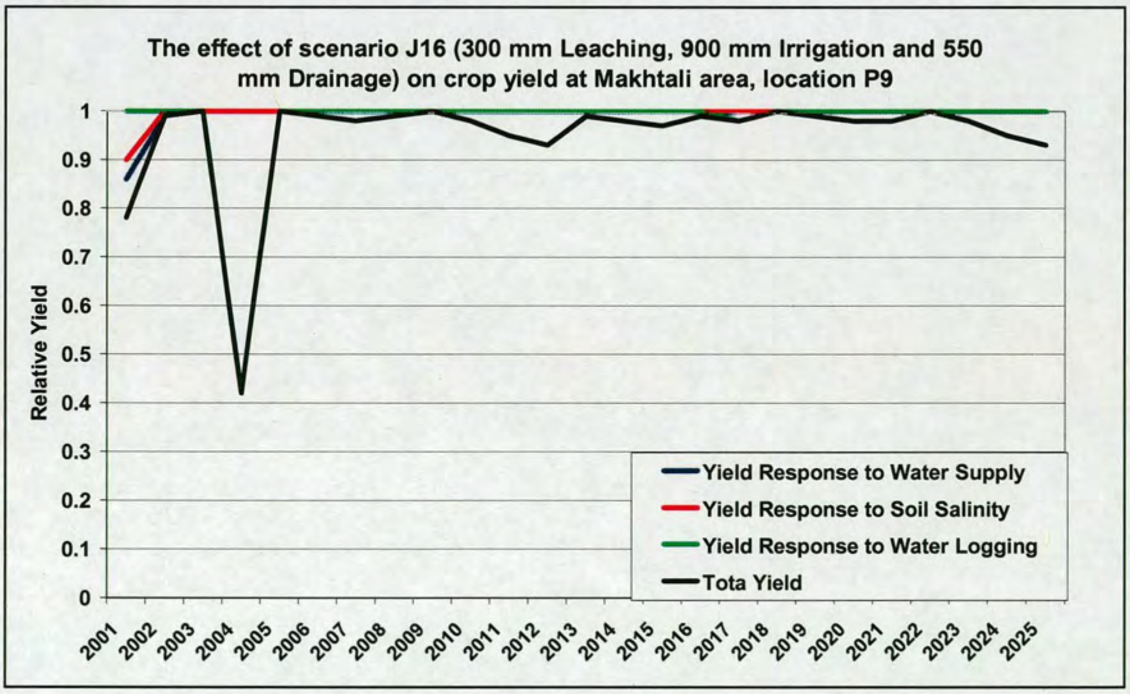
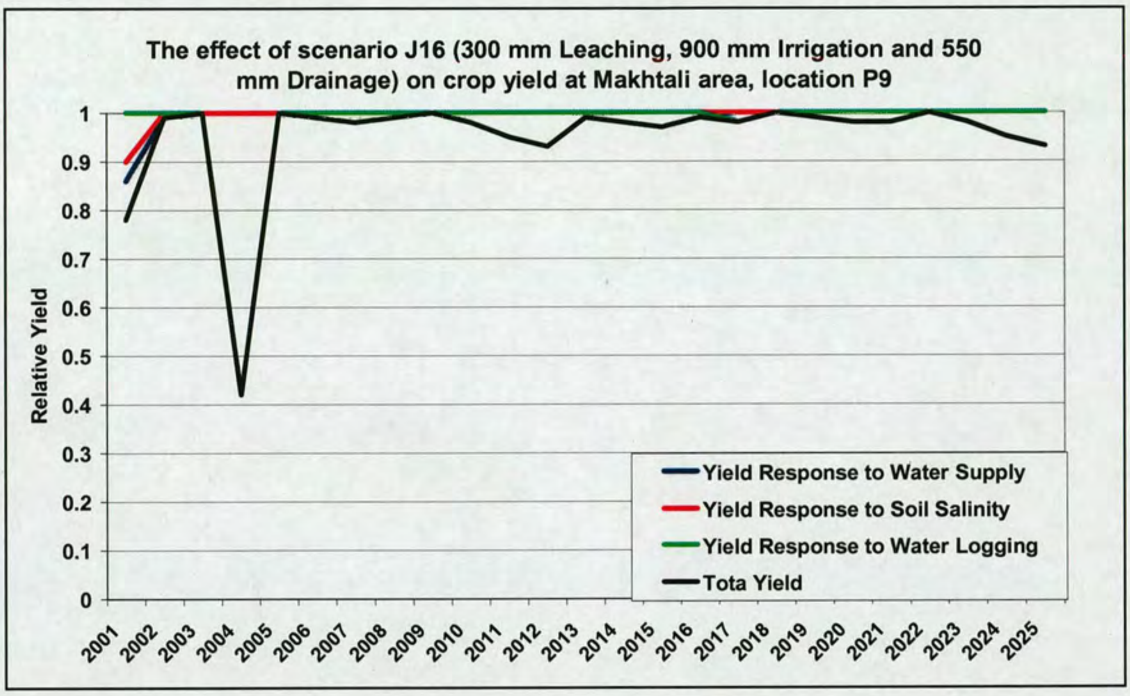
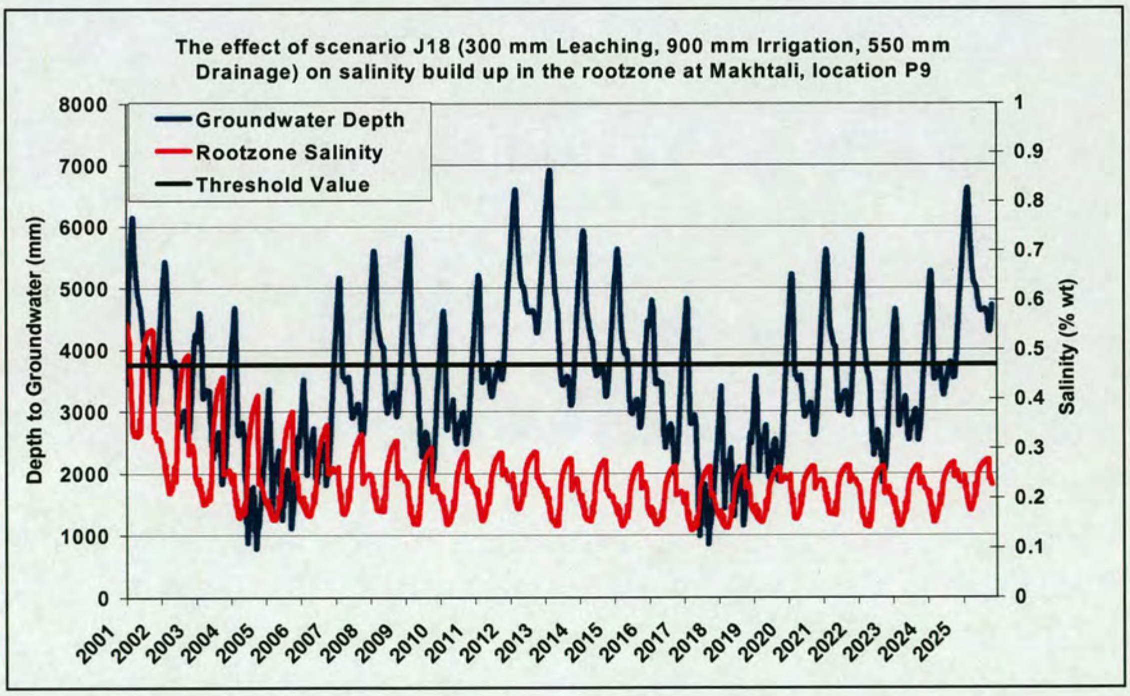






MAKHTALI AREA, LOCATION P9



E. The Prediction Run Output

The following tables include the matrix program results. Results are presented in terms of yield response to water supply, salinity and waterlogging as well as to the combined effect of these. It also includes the sustainability tables for the representative sites which indicate which of the optimum irrigation and drainage combinations are sustainable and which are not. Cost-Benefit Index tables are also included.

KARAOI AREA, LOCATION P3
TOTAL YIELD, AVERAGE OVER LAST 10 YEARS OF SIMULATION

IRRIG SCEN.	DRAINAGE SCENARIO 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
A	0.00	0.63	0.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B	0.00	0.58	0.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.00	0.00	0.00	0.00	0.71	0.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D	0.00	0.00	0.00	0.00	0.00	0.00	0.80	0.79	0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E	0.00	0.00	0.00	0.00	0.88	0.88	0.76	0.76	0.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F	0.00	0.00	0.00	0.00	0.00	0.88	0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.90	0.88	0.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.90	0.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.91	0.89	0.00
J	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.93	0.00	0.00

KARAOI AREA, LOCATION P3
YIELD RESPONSE TO WATER SUPPLY, AVERAGE OVER LAST 10 YEARS OF SIMULATION

IRRIG. SCEN.	DRAINAGE SCENARIO 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
A	0.00	0.63	0.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B	0.00	0.58	0.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.00	0.00	0.00	0.00	0.71	0.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D	0.00	0.00	0.00	0.00	0.00	0.00	0.80	0.79	0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E	0.00	0.00	0.00	0.00	0.91	0.90	0.77	0.77	0.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F	0.00	0.00	0.00	0.00	0.00	0.89	0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.90	0.90	0.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.90	0.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.91	0.90	0.00
J	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.93	0.00	0.00

KARAOI AREA, LOCATION P3
YIELD RESPONSE TO SALINITY, AVERAGE OVER LAST 10 YEARS OF SIMULATION

IRRIG. SCEN.	DRAINAGE SCENARIO 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
A	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00
J	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00

KARAOI AREA, LOCATION P3
YIELD RESPONSE TO WATERLOGGING, AVERAGE OVER LAST 10 YEARS OF SIMULATION

IRRIG. SCEN.	DRAINAGE SCENARIO 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
A	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E	0.00	0.00	0.00	0.00	0.98	0.98	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F	0.00	0.00	0.00	0.00	0.00	0.98	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.98	0.98	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.99	0.00
J	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00

KARAOI AREA, LOCATION P3
SUSTAINABILITY, AVERAGE OVER LAST 10 YEARS OF SIMULATION

Y = UNSUSTAINABLE, S = SUSTAINABLE

IRRIG. SCEN.	DRAINAGE SCENARIO 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
A	-	Y	Y	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B	-	Y	Y	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C	-	-	-	-	Y	Y	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D	-	-	-	-	-	-	Y	Y	Y	-	-	-	-	-	-	-	-	-	-	-	-
E	-	-	-	-	Y	Y	Y	Y	Y	-	-	-	-	-	-	-	-	-	-	-	-
F	-	-	-	-	-	Y	Y	-	-	-	-	-	-	-	-	-	-	-	-	-	-
G	-	-	-	-	-	-	-	-	-	Y	Y	Y	-	-	-	-	-	-	-	-	-
H	-	-	-	-	-	-	-	-	-	Y	Y	-	-	-	-	-	-	-	-	-	-
I	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Y	Y	-
J	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Y	-	-

KARAOI AREA, LOCATION P3
COST-BENEFIT INDEX, AVERAGE OVER LAST 10 YEARS OF SIMULATION

IRRIG. SCEN.	DRAINAGE SCENARIO 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
A	0.00	62.00	55.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B	0.00	57.40	57.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.00	00.00	0.00	0.00	69.10	68.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D	0.00	0.00	0.00	0.00	0.00	0.00	77.40	76.50	75.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E	0.00	0.00	0.00	0.00	86.40	86.30	74.30	74.30	74.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F	0.00	0.00	0.00	00.00	0.00	85.80	74.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	87.40	85.00	84.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	87.30	86.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	87.20	85.10	0.00
J	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	88.90	0.00	0.00

BIRLIK AREA, LOCATION P3
TOTAL YIELD, AVERAGE OVER LAST 10 YEARS OF SIMULATION

IRRIG.	DRAINAGE SCENARIO																				
SCEN.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
A	0.00	0.00	0.55	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B	0.00	0.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.00	0.00	0.00	0.71	0.71	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D	0.00	0.00	0.00	0.00	0.00	0.00	0.79	0.79	0.79	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F	0.00	0.00	0.00	0.00	0.84	0.85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.87	0.88	0.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.95	0.84	0.86	0.00	0.00	0.00
J	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.98	0.96	0.00	0.00	0.00	0.00

BIRLIK AREA, LOCATION P3
YIELD RESPONSE TO WATER SUPPLY, AVERAGE OVER LAST 10 YEARS OF SIMULATION

IRRIG.	DRAINAGE SCENARIO																				
SCEN.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
A	0.00	0.00	0.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B	0.00	0.54	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.00	0.00	0.00	0.71	0.71	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D	0.00	0.00	0.00	0.00	0.00	0.00	0.79	0.79	0.79	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F	0.00	0.00	0.00	0.00	0.89	0.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.87	0.88	0.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.95	0.95	0.94	0.00	0.00	0.00
J	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.98	0.97	0.00	0.00	0.00	0.00

BIRLIK AREA, LOCATION P3
YIELD RESPONSE TO SALINITY, AVERAGE OVER LAST 10 YEARS OF SIMULATION

IRRIG.	DRAINAGE SCENARIO																				
SCEN.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
A	0.00	0.00	0.99	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B	0.00	0.95	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00
J	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00

BIRLIK AREA, LOCATION P3
YIELD RESPONSE TO WATERLOGGING, AVERAGE OVER LAST 10 YEARS OF SIMULATION

IRRIG.	DRAINAGE SCENARIO																				
SCEN.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
A	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F	0.00	0.00	0.00	0.00	0.95	0.97	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.89	0.92	0.00	0.00	0.00
J	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.98	0.00	0.00	0.00	0.00

BIRLIK AREA, LOCATION P3
SUSTAINABILITY, AVERAGE OVER LAST 10 YEARS OF SIMULATION

Y = UNSUSTAINABLE, S = SUSTAINABLE

IRRIG.	DRAINAGE SCENARIO																				
SCEN.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
A	-	-	S	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B	-	S	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C	-	-	-	S	S	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D	-	-	-	-	-	-	S	S	S	-	-	-	-	-	-	-	-	-	-	-	-
E	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
F	-	-	-	-	S	S	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
G	-	-	-	-	-	-	-	-	-	S	S	S	-	-	-	-	-	-	-	-	-
H	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
I	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	S	S	S	-	-	-
J	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	S	S	-	-	-	-

COST-BENEFIT INDEX, AVERAGE OVER LAST 10 YEARS OF SIMULATION

IRRIG.	DRAINAGE SCENARIO																				
SCEN.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
A	0.00	0.00	54.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B	0.00	50.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.00	0.00	0.00	69.80	69.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D	0.00	0.00	0.00	0.00	0.00	0.00	77.00	76.80	76.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F	0.00	0.00	0.00	0.00	81.50	83.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	84.60	84.70	84.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	91.30	80.60	82.50	0.00	0.00	0.00
J	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	94.00	92.30	0.00	0.00	0.00	0.00

MAKHTALI AREA, LOCATION P9
TOTAL YIELD, AVERAGE OVER LAST 10 YEARS OF SIMULATION

IRRIG.	DRAINAGE SCENARIO																				
SCEN.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
A	0.00	0.54	0.54	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B	0.00	0.52	0.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.90	0.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.83	0.84	0.00	0.00	0.00
J	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.98	0.83	0.84	0.00	0.00	0.00

MAKHTALI AREA, LOCATION P9
YIELD RESPONSE TO WATER SUPPLY, AVERAGE OVER LAST 10 YEARS OF SIMULATION

IRRIG.	DRAINAGE SCENARIO																				
SCEN.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
A	0.00	0.59	0.59	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B	0.00	0.58	0.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.90	0.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.97	0.96	0.00	0.00	0.00
J	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.98	0.98	0.98	0.00	0.00	0.00

MAKHTALI AREA, LOCATION P9
YIELD RESPONSE TO SALINITY, AVERAGE OVER LAST 10 YEARS OF SIMULATION

IRRIG.	DRAINAGE SCENARIO																				
SCEN.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
A	0.00	0.91	0.92	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B	0.00	0.89	0.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00
J	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00

MAKHTALI AREA, LOCATION P9
YIELD RESPONSE TO WATERLOGGING, AVERAGE OVER LAST 10 YEARS OF SIMULATION

IRRIG.	DRAINAGE SCENARIO																				
SCEN.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
A	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.86	0.88	0.00	0.00	0.00
J	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.85	0.86	0.00	0.00	0.00

MAKHTALI AREA, LOCATION P9
SUSTAINABILITY, AVERAGE OVER LAST 10 YEARS OF SIMULATION

Y = UNSUSTAINABLE, S = SUSTAINABLE

IRRIG.	DRAINAGE SCENARIO																				
SCEN.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
A	-	S	S	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B	-	S	S	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
E	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
F	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
G	-	-	-	-	-	-	-	-	-	-	S	S	-	-	-	-	-	-	-	-	-
H	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
I	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	S	S	-	-	-
J	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	S	S	S	-	-	-

MAKHTALI AREA, LOCATION P9
COST-BENEFIT INDEX, AVERAGE OVER LAST 10 YEARS OF SIMULATION

IRRIG.	DRAINAGE SCENARIO																				
SCEN.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
A	0.00	52.70	53.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B	0.00	50.80	51.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.00	00.00	00.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	86.90	86.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	79.40	80.80	0.00	0.00	0.00
J	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	94.30	79.40	80.50	0.00	0.00	0.00